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Bulletins 1 to 15

Structural Materials Research Laboratory
Lewis Institute
Chicago

Experimental Studies of Concrete

These researches in the properties of concrete and concrete materials were carried out through the co-operation of the Lewis Institute and the Portland Cement Association

PHILADELPHIA

1918-1925

LIST OF BULLETINS

BULLETIN 1.—Design of Concrete Mixtures, by Duff A. Abrams (1918).
Revised Edition, 1925.

BULLETIN 2.—Effect of Curing Condition on Wear and Strength of Concrete, by Duff A. Abrams.
Reprinted from Proceedings of the American Railway Engineering Association, 1919.

BULLETIN 3.—Effect of Vibration, Jigging and Pressure on Fresh Concrete, by Duff A. Abrams.
Reprinted from Proceedings of the American Concrete Institute, 1919.

BULLETIN 4.—Effect of Fineness of Cement, by Duff A. Abrams.
Reprinted from Proceedings of the American Society for Testing Materials, 1919.
Revised Edition, 1922.

BULLETIN 5.—Modulus of Elasticity of Concrete, by Stanton Walker.
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Revised Edition, 1923.

BULLETIN 6.—Effect of Storage of Cement, by Duff A. Abrams (1920).
Second Edition, 1924.

BULLETIN 7.—Effect of Tannic Acid on Strength of Concrete, by Duff A. Abrams.
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BULLETIN 8.—Effect of Hydrated Lime and Other Powdered Admixtures in Concrete, by Duff A. Abrams.
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Revised Edition, 1925.

BULLETIN 9.—Quantities of Materials for Concrete, by Duff A. Abrams and Stanton Walker (1921).
Second Edition, 1925.

BULLETIN 10.—Wear Tests of Concrete, by Duff A. Abrams.
Reprinted from Proceedings of the American Society for Testing Materials, 1921.

BULLETIN 11.—Flexural Strength of Plain Concrete, by Duff A. Abrams.
Reprinted from Proceedings of the American Concrete Institute, 1922.

BULLETIN 12.—Tests of Impure Waters for Mixing Concrete, by Duff A. Abrams.
Reprinted from Proceedings of the American Concrete Institute, 1924.

BULLETIN 13.—Calcium Chloride as an Admixture in Concrete, by Duff A. Abrams.
Reprinted from Proceedings of the American Society for Testing Materials, 1924.

BULLETIN 14.—Effect of End Condition of Cylinder on Compressive Strength of Concrete, by Harrison F. Gonnerman.
Reprinted from Proceedings of the American Society for Testing Materials, 1924.

BULLETIN 15.—Studies of Curing Concrete in a Semi-Arid Climate, by Harrison F. Gonnerman and C. L. McKesson (1925).
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Bulletin 1

Structural Materials Research Laboratory
Lewis Institute
Chicago

Design of Concrete Mixtures

By

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Professor in Charge of Laboratory

Published by the

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First Printing, December, 1918
Revised Edition, December, 1925

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Foreword to Revised Edition

The report on "Design of Concrete Mixtures" was originally published in the Minutes of the Annual Meeting of the Portland Cement Association, held in New York City, December, 1918.

In this revised edition the following changes have been made:

(a) All tables and figures placed after the text.

(b) Equations (4) and (5) were changed so that the absorption of the aggregate is independent of the relative consistency of the concrete; in other words, the factor (a — c) is not multiplied by the relative consistency. The quantities of mixing water in Table 4 have been revised in accordance with this change. The table was also modified by making no allowance for absorption of aggregate.

(c) Footnotes added on p. 7, 9 and 14 on the new method of making slump test.

(d) Original Table 4 omitted; former Table 5 now becomes Table 4.

For further discussion of methods of designing concrete mixtures and recent applications to construction work, see:

"Quantities of Materials for Concrete," by Abrams and Walker; Bulletin 9 of this Laboratory, 1921; Second Edition, 1925.
Tables of proportions and quantities of cement, water and aggregates required to produce concrete of 2000, 2500, 3000, 3500 and 4000 lb. per sq. in. at 28 days.

"Field Tests of Concrete," by Ahlers and Walker; Proc. Am. Concrete Inst., v. 20, p. 358, 1924.
Field tests on 5 large reinforced concrete projects carried out in New York City in cooperation with the New York group of contractors.

"Report on Field Tests of Concrete Used on Construction Work," by Slater and Walker; Proc. Am. Soc. Civil Eng., January, 1925. Summary, Proc. Am. Concrete Inst., v. 20, p. 420, 1924.
Field tests of concrete used in a large reinforced concrete building for the Victor Talking Machine Co., Camden, N. J., and in the piers of the bridge of the Central Railroad of New Jersey across Newark Bay, made in cooperation with the Joint Committee on Standard Specifications for Concrete and Reinforced Concrete, the Joint Committee of Contractors, and the U. S. Bureau of Standards.

"Water-Ratio Specification for Concrete," by McMillan and Walker. Paper presented before Am. Soc. Civil Eng., October, 1925.
Outlines method for specifying and controlling quality of concrete by means of water-ratio. Data from which estimates of quantities of materials required for different qualities of concrete can be made. Appendix gives specification for concrete on water-ratio basis which is being used on building under construction in Chicago.

For examples of the application of these principles by other engineers, see:

"Old and New Methods for Constructing Concrete Bridges," by J. B. Hunley; Proc. Am. Concrete Inst., v. 20, p. 259, 1924. Eng. and Contr., March 28, April 23 and May 28, 1924.
Method of proportioning field concrete by the Big Four Railway on bridges built at Beach Grove and Sidney, Ohio.

"Abrams' Theory in Practice," by P. E. Kressly; Western Highways Builder, May and July, 1924.
Use in road construction in California.

"Aggregates and Water-Cement Ratios"; Eng. and Contr., v. 63, p. 866, April 24, 1925; from "Instructions to Fieldmen for Making Concrete," by Bronx Parkway Commission.

"Design of Concrete Mixtures," by T. P. Watson; Proc. Am. Concrete Inst., v. 21, 1925. Abstract, Railway Review, v. 76, p. 845, May 9, 1925.
Data on experience in field control on Beck's Run Bridge near Pittsburgh.

DESIGN OF CONCRETE MIXTURES

By DUFF A. ABRAMS

The design of concrete mixtures is a subject of vital interest to all engineers and constructors who have to do with concrete work. The problem involved may be one of the following:

1. What mix is necessary to produce concrete of proper strength for a given work?
2. With given materials what proportions will give the best concrete at minimum cost?
3. With different lots of materials of different characteristics which is best suited for the purpose?
4. What is the effect on strength of concrete from changes in mix, consistency or size and grading of aggregate?

Proportioning concrete frequently involves selection of materials as well as their combination. In general, the question of relative costs is also present.

The term "Design" is used in the title of this article as distinguished from "proportioning" since it is the intention to imply that each element of the problem is approached with a deliberate purpose in view which is guided by a rational method of accomplishment.

The design of concrete mixtures, with a view to producing a given result in the most economic manner, involves many complications which have heretofore defied analysis.

Many different methods of proportioning have been suggested; the most important ones may be characterized as follows:

1. Arbitrary selection, such as 1:2:4 mix, without reference to the size or grading of the fine and coarse aggregate;
2. Density of aggregates in which the endeavor is made to secure an aggregate of maximum density;
3. Density of concrete in which the attempt is made to secure concrete of maximum density;
4. Sieve analysis, in which the grading of the aggregates is made to approximate some predetermined sieve analysis curve which is considered to give the best results;
5. Surface area of aggregates.

It is a matter of common experience that the method of arbitrary selection in which fixed quantities of fine and coarse aggregates are mixed without regard to the size and grading of the individual materials, is far from satisfactory. Our experiments have shown that the other methods mentioned above are also subject to serious limitations. We have found that the maximum strength of concrete does not depend on either an aggregate of maximum density or a concrete of maximum density, and that the methods which have been suggested for proportioning concrete by reference to a fixed sieve analysis are based on an erroneous theory. The methods of proportioning concrete which have been proposed in the past have failed to give proper attention to the water content of the mix. Our experimental work has emphasized the importance of the water in concrete mixtures, and shown that the water is, in fact, the most important ingredient, since very small variations in water content produce more important variations in the strength and other properties of concrete than similar changes in the other ingredients.

New Studies of Concrete Mixtures

During the past three years a large number of investigations have been under way at the Structural Materials Research Laboratory, Lewis Institute, Chicago, which throw considerable new light on the subject of proportioning concrete. These investigations are being carried out through the cooperation of the Institute and

the Portland Cement Association. These studies have covered an investigation of the inter-relation of the following factors:

1. The consistency (quantity of mixing water).
2. The size and grading of aggregates.
3. The mix (proportion of cement).

Any comprehensive study of proportioning concrete must take into account all of these factors.

During this period about 50,000 tests have been carried out which have a bearing on this subject. These tests have been largely confined to compression tests of concrete and mortars. These investigations have given us a new insight into the factors which underlie the correct proportioning of concrete mixtures and show the limitations of older methods. Certain phases of these investigations are still under way.

The following may be mentioned as among the most important principles which have been established with reference to the design of concrete mixtures. In a brief report of this kind it is impracticable to present more than an outline of the methods of applying the principles to practical problems. In only a few instances are experimental data given on which these conclusions are based.

1. With given concrete materials and conditions of test the quantity of mixing water used determines the strength of the concrete, so long as the mix is of a workable plasticity.
2. The sieve analysis furnishes the only correct basis for proportioning aggregates in concrete mixtures.
3. A simple method of measuring the effective size and grading of an aggregate has been developed. This gives rise to a function known as the "fineness modulus" of the aggregate.
4. The fineness modulus of the aggregate furnishes a rational method for combining materials of different size for concrete mixtures.
5. The sieve analysis curve of the aggregate may be widely different in form without exerting any influence on the concrete strength.
6. Aggregate of equivalent concrete-making qualities may be produced by an infinite number of different gradings of a given material.
7. Aggregates of equivalent concrete-making qualities may be produced from materials of widely different size and grading.
8. In general, fine and coarse aggregates of widely different size or grading can be combined in such a manner as to produce similar results in concrete.
9. The aggregate grading which produces the strongest concrete is not that giving the maximum density (lowest voids). A grading coarser than that giving maximum density is necessary for highest concrete strength.
10. The richer the mix, the coarser the grading should be for an aggregate of given maximum size; hence, the greater the discrepancy between maximum density and best grading.
11. A complete analysis of the water-requirements of concrete shows that the quantity of mixing water required is governed by the following factors:
    (a) The condition of "plasticity" or "workability" of concrete which must be used—the relative consistency;
    (b) The normal consistency of the cement;
    (c) The size and grading of the aggregate;
    (d) The relative volumes of cement and aggregate—the mix;
    (e) The absorption of the aggregate;
    (f) The contained water in aggregate.
12. There is an intimate relation between the grading of the aggregate and the quantity of water required to produce a workable concrete.

13. The water content of a concrete mix is best considered in terms of the volume of the cement—the water-ratio.

14. The shape of the particle and the quality of the aggregate have less influence on the concrete strength than has been reported by other experimenters.

Effect of Quantity of Mixing Water on the Strength of Concrete

Fig. 1 shows the relation between the compressive strength and the water content for 28-day tests of 6 by 12-in. concrete cylinders. Mixes from 1:15 to neat cement were used; each mix was made up of aggregates ranging in size from 14-mesh sand up to 1½-in. gravel; a wide range in consistencies was used for all mixes and gradings.

The water content of the concrete is expressed as a ratio to the volume of cement, considering that the cement weighs 94 lb. per cu. ft. Distinguishing marks are used for each mix, but no distinction is made between aggregates of different size or different consistencies.

When the compressive strength is platted against the water ratio in this way, a smooth curve is obtained, due to the overlapping of the points for different mixes. Values from dry concretes have been omitted. If these were used we should obtain a series of curves dropping downward and to the left from the curve shown. It is seen at once that the size and grading of the aggregate and the quantity of cement are no longer of any importance except in so far as these factors influence the quantity of water required to produce a workable mix. This gives us an entirely new conception of the function of the constituent materials entering into a concrete mix and is the most basic principle which has been brought out in our studies of concrete.

The equation of the curve is of the form,

$$S = \frac{A}{B^x} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where S is the compressive strength of concrete and x is the ratio of the volume of water to the volume of cement in the batch. A and B are constants whose values depend on the quality of the cement used, age of the concrete, curing conditions, etc.

This equation expresses the law of strength of concrete so far as the proportions of materials are concerned. It is seen that for given concrete materials the strength depends on only one factor—the ratio of water to cement. Equations which have been proposed in the past for this purpose contain terms which take into account such factors as quantity of cement, proportions of fine and coarse aggregate, voids in aggregate, etc., but they have uniformly omitted the only term which is of any importance; that is, *the water.*

For the conditions of these tests, equation (1) becomes,

$$S = \frac{14{,}000}{7^x} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

The relation given above holds so long as the concrete is not too dry for maximum strength and the aggregate not too coarse for a given quantity of cement; in other words, so long as we have a *workable mix.*

Other tests made in this laboratory have shown that the character of the aggregate makes little difference so long as it is clean and not structurally deficient. The absorption of the aggregate must be taken into account if comparison is being made of different aggregates.

The strength of the concrete responds to changes in water, regardless of the reason for these changes. The water-ratio may be changed due to any of the following causes:

1. Change in mix (cement content).
2. Change in size or grading of aggregate.
3. Change in relative consistency.
4. Any combination of (1) to (3).

In certain instances a 1:9 mix is as strong as a 1:2 mix, depending only on water content. It should not be concluded that these tests indicate that lean mixes can be substituted for richer ones without limit. We are always limited by the necessity of using sufficient water to secure a workable mix. So in the case of the grading of aggregates. The workability of the mix will in all cases dictate the minimum quantity of water that can be used. The importance of the workability factor in concrete is therefore brought out in its true relation.

The problem of designing concrete mixes resolves itself into this:

To produce a workable concrete which has a given water-ratio using a minimum quantity of cement; or the converse, to produce a workable concrete with a minimum water-ratio using a given quantity of cement. The methods for securing the best grading of aggregate and the use of the driest concrete which is workable are thus seen to be only devices which enable us to accomplish the above-mentioned results.

Fineness Modulus of Aggregate

The experimental work carried out in the laboratory has given rise to what we term the fineness modulus of the aggregate. This function furnishes a method of measuring the size and grading of the aggregate. It may be defined as follows:

The sum of the percentages in the sieve analysis of the aggregate divided by 100.

The sieve analysis is determined by using the following sieves from the Tyler standard series: 100, 48, 28, 14, 8, 4, ⅜-in., ¾-in. and 1½-in. These sieves are made of square-mesh wire cloth. Each sieve has a clear opening just double the width of the preceding one. The exact dimensions of the sieves and the method of determining the fineness modulus will be found in Table 1. It will be noted that the sieve analysis is expressed in terms of the percentages of material by volume or weight *coarser than* each sieve.

A well-graded torpedo sand up to No. 4 sieve will give a fineness modulus of about 3.00; a coarse aggregate graded 4-1½ in. will give fineness modulus of about 7.00; a mixture of the above materials in proper proportions for a 1:4 mix will have a fineness modulus of about 5.80. A fine sand such as drift-sand may have a fineness modulus as low as 1.50.

Sieve Analysis of Aggregates

There is an intimate relation between the sieve analysis curve for the aggregate and the fineness modulus; in fact, the fineness modulus enables us for the first time to properly interpret the sieve analysis of an aggregate. If the sieve analysis of an aggregate is platted in the manner indicated in Fig. 2; that is, using the per cent coarser than a given sieve as ordinate, and the sieve size (platted to logarithmic scale) as abscissa, the fineness modulus of the aggregate is measured by the area below the sieve analysis curve. The dotted rectangles for aggregate "G" show how this result is secured. Each elemental rectangle is the fineness modulus of the material of that particular size. The fineness modulus of the graded aggregate is then the summation of these elemental areas. Any other sieve analysis curve which will give the same total area corresponds to the same fineness modulus and will require the same quantity of water to produce a mix of the same plasticity and gives concrete of the same strength, so long as it is not too coarse for the quantity of cement used.

The fineness modulus may be considered as an abstract number; it is in fact a summation of volumes of material. There are several different methods of computing it, all of which will give the same result. The method given in Table 1 is probably the simplest and most direct.

Some of the mathematical relations involved are of interest. The following expression shows the relation between the fineness modulus and the size of the particle:

$$m = 7.94 + 3.32 \log d \quad \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

where m = fineness modulus

d = diameter of particle in inches

This relation is perfectly general so long as we use the standard set of sieves mentioned above. The constants are fixed by the regular sizes of sieves used and the units of measure. Logarithms are to the base 10.

This relation applies to a single-size material or to a given particle. The fineness modulus is then a logarithmic function of the diameter of the particle. This formula need not be used with a graded material, since the value can be secured more easily and directly by the method used in Table 1. It is applicable to graded materials provided the relative quantities of each size are considered, and the diameter of each group is used. By applying the formula to a graded material we would be calculating the values of the separate elemental rectangles shown in Fig. 2.

Fineness Modulus Strength Relation for Concrete

Many different series of tests have shown that for a given plastic condition of concrete and the same mix there is an intimate relation between the fineness modulus of the aggregate and the strength and other properties of the concrete. We have seen that the reason for this result is found in the fact that the fineness modulus simply reflects the changes in water-ratio necessary to produce a given plastic condition.

Figs. 3 and 4 give the results of certain compression tests which bring out the relation between the strength of the concrete and the fineness modulus of the aggregate. It will be noted from Fig. 3 that a separate curve may be drawn for each mix. In each case there is a steady increase in the compressive strength of the concrete as the fineness modulus of the aggregate increases, until a certain value is reached which corresponds to a maximum point. It will be noted also that this maximum point corresponds to higher and higher values of fineness modulus as the quantity of cement in the mix is increased. In other words, the maximum strength comes at a fineness modulus of about 5.80 for the 1:9 mix and about 6.40 for the 1:4 mix. In these tests the different values of the fineness modulus were secured by using a preponderance of the coarser sizes, but in all cases maintaining the same limiting size, that is, 1¼ in.

In Fig. 4 is found a similar relation between the strength and the fineness modulus, except that no maximum point is found. This condition arises from the fact that the maximum size of the aggregate is increasing without changing the type of the sieve analysis curve, consequently the fineness modulus strength curve continues to rise indefinitely. The height to which the curve rises is limited only by the maximum size of aggregate which may be used. It is important to note that there is no conflict between the indications of Figs. 3 and 4.

For all practical purposes and for ordinary ranges in concrete mixes the fineness modulus strength relation may be assumed as a linear one. The comparison of the true and approximate relation is brought out in the discussion of the "Water Formula" below.

A given value for the fineness modulus of an aggregate can be secured with any combination of percentages in the sieve analysis which gives the same total, consequently, an infinite variety of gradings may be found which give aggregate of the same concrete strength. Table 2 gives the results of groups of tests which bring out the wide variation which may be made in the grading of aggregate without producing any essential variation in the concrete strength. Twenty-seven different gradings of the same aggregate were made up. These gradings covered the widest possible range, but they had one property in common; that is, a fineness modulus of 6.04. All specimens were mixed with the same quantity of cement and water. Separate sets of specimens were made of two different consistencies. The mean variation from the average strength is about 3%.

Table 2 also furnishes some interesting data on the surface-area method of proportioning aggregates. It is seen that there is the widest variation in the surface area of the aggregate without any appreciable difference in the concrete strength. Our studies have clearly shown that surface area is not a satisfactory basis for proportioning aggregates.

Design of Concrete Mixes

In accordance with our previous statements the problem of designing concrete mixes using given materials resolves itself into that of finding the combination which with a given water-ratio will give a concrete of suitable workability using a minimum of cement.

The following outline will make clear the steps to be followed in the design of concrete mixes on the basis of our studies of concrete:

STEPS IN THE DESIGN OF CONCRETE MIXTURES

1. Knowing the compressive strength required of the concrete, determine by reference to Fig. 1 the maximum water-ratio which may be used. Subsequent steps in the design of concrete mixes are only devices for securing a workable concrete using this water-ratio and a minimum quantity of cement. It is obvious that a given water-ratio can be secured with a minimum of cement if the aggregate is graded as coarse as permissible (considering its size and the mix used) and if we use the driest mix which can be properly placed. Securing a coarse, well-graded aggregate, using rich mixes, employing the driest practicable consistency, using mechanical methods of placing concrete, etc., are all methods of producing a workable mix with a minimum water-ratio. Experience or trial is the only guide in determining the relative consistency of concrete necessary in the work. Obviously the driest workable consistency should be used. The size of aggregate available, or which must be used, and the other factors will furnish a guide as to the mix. The mix is expressed as one volume of cement to a given number of volumes of aggregate; that is, the combined fine and coarse aggregate. In general, some allowance must be made for the high strengths in laboratory tests. In other words, a water-ratio somewhat lower than that given for the required strength in Fig. 1 should be used. For convenience in the subsequent steps we shall deal with concrete strength instead of water-ratio (as in Fig. 6), although it should be understood that it is the water-ratio which fixes the strength so long as we have a plastic mix.
2. Make sieve analysis of fine and coarse aggregates, using Tyler standard sieves of the following sizes: 100, 48, 28, 14, 8, 4, ⅜, ¾ and 1½ in. Express sieve analysis in terms of percentages of material by weight (or separate volumes) *coarser than* each of the standard sieves.
3. Compute fineness modulus of each aggregate by adding the percentages found in (2), and dividing by 100.
4. Determine the "maximum size" of aggregate by applying the following rules: If more than 15% of aggregate is coarser than any sieve the maximum size shall be taken as the next larger sieve in the standard set; if less than 15% is coarser than certain sieves, the smallest of these sieve sizes shall be considered the maximum size.
5. From Table 3 determine the maximum value of fineness modulus which may be used for the mix, kind and size of aggregate, and the work under consideration. (The values in Table 3 are platted in Fig. 5.)
6. Compute the percentages of fine and coarse aggregates required to produce the fineness modulus desired for the final aggregate mixture by applying the formula:

$$p = 100\frac{A - B}{A - C} \qquad (3)$$

where p = percentage of fine aggregate in total mixture.
A = fineness modulus of coarse aggregate.
B = fineness modulus of final aggregate mixture.
C = fineness modulus of fine aggregate.

Fig. 7 may be used for solving Equation 3, and for making comparisons of the effect of certain changes in proportions of fine and coarse aggregates. The distinction between fine and coarse aggregate is solely for convenience in securing a uniform grading; the division may be made at any desired point.

7. With the estimated mix, fineness modulus and consistency enter Fig. 6 and determine the strength of concrete produced by the combination. If the strength shown by the diagram is not that required, the necessary readjustment may be made by changing the mix, consistency or size and grading of the aggregates.

The quantity of water required can be determined from Formula 4 below, or approximately from Table 4.

IMPORTANT NOTE: It must be understood that the values in Fig. 6 were determined from compression tests of 6 by 12-in. cylinders stored for 28 days in a damp place. The values obtained on the work will depend on such factors as the consistency of the concrete, quality of the cement, methods of mixing, handling, placing the concrete, etc., and on age and curing conditions.

Strength values higher than given for relative consistency of 1.10 should seldom be considered in designing, since it is only in exceptional cases that a consistency drier than this can be satisfactorily placed. For wetter concrete much lower strengths must be considered.

Calculation of Water Required for Concrete

Because of the important influence of the quantity of water in the concrete it is desirable to have a sound basis for proportioning the water. The quantity of water necessary for given proportions and conditions may be determined by the following formula:

$$x = R\left[\frac{3}{2}p + \frac{.30n}{1.26^m}\right] + (a - c)\,n \quad \ldots\ldots\ldots (4)$$

where x = water required—ratio to volume of cement in batch (water-ratio).

R = Relative consistency of concrete, or "workability factor". Normal consistency (relative consistency = 1.00) requires the use of such a quantity of mixing water as will cause a slump of ½ to 1 in. in a freshly molded 6 by 12-in. cylinder* of about 1:4 mix upon withdrawing the form by a steady, upward pull. A relative consistency of 1.10 requires the use of 10% more water and under the above conditions will give a slump of about 5 to 6 in.

p = Normal consistency of cement (ratio by weight).

m = Fineness modulus of aggregate (an exponent).

n = Volumes of mixed aggregate to one of cement (the mix).

a = Absorption of aggregate, ratio of water absorbed to volume of aggregate. (Determined after immersion in water for 3 hours. Average values for crushed limestone and pebbles may be assumed as 0.02; porous sandstones may reach 0.08; very light and porous aggregate may reach 0.25.)

c = Moisture contained in aggregate, ratio of water contained to volume of aggregate. (Assume as zero for room-dry aggregate.)

*Present practice in making the slump test for workability of concrete requires the use of a truncated cone, 4 in. top diameter, 8 in. bottom diameter and 12 in. high. For concrete of the usual range of workability the cone gives slumps about 2/3 that of the cylinder. The truncated cone is specified in the "Report of the Joint Committee on Standard Specifications for Concrete and Reinforced Concrete" and in the "Tentative Method of Test for Consistency of Portland Cement Concrete" (Serial Designation: D138-25T) of the American Society for Testing Materials. (Note added December, 1925.)

This formula takes account of all the factors which affect the quantity of water required in a concrete mixture. These factors may be classified as follows:

1. "Workability" factor, or the relative consistency of the concrete. This is dictated by the kind of work being done; concrete must be more plastic (which generally means a wetter consistency) in reinforced concrete building construction than is necessary in mass work. The term (R) in the equation takes care of this factor. (R) may vary from, say, 0.90 for a dry concrete to 2.00 or higher for very wet mixes.
2. Cement factor, which is made up of two parts: the *quality* of cement so far as normal consistency is concerned (p); the *quantity* of cement in the mix (n).
3. The aggregate factor. This includes the three terms within the parenthesis in Equation 4. The first term, involving (m), takes account of the size and grading; the second (a) the absorption, and the third (c) the water contained in the aggregate.

In case admixtures of any kind are used, another term must be inserted in the equation. This relation has been fully worked out, but is not included in this report.

Simplified Water Formula

While Equation (4) represents the true water relation, it is somewhat complicated by the fact that the fineness modulus (m) appears as an exponent. The equation can be expressed in a simpler form as follows:

$$x = R\left[\frac{3}{2}p + 0.22n - \frac{mn}{42}\right] + (a - c)\,n \quad \ldots\ldots\ldots (5)$$

This equation gives values for ordinary ranges of mix and grading of aggregate which are sensibly the same as given by Equation (4).

Maximum Permissible Values of Fineness Modulus of Aggregates

Since a maximum practicable value of fineness modulus is found for each size of aggregate and mix, it is necessary to place certain limits on the value which may be used for proportioning materials for concrete mixes. Table 3 gives limits which will be found practicable. Subsequent experience may dictate certain modifications in the details.

The purpose of Table 3 is to avoid the attempt to secure an aggregate grading which is too coarse for its maximum size and for the amount of cement used. It is also useful in prohibiting attempts to use sands which are too coarse for best results in concrete mixtures. For instance, it would be found from this table that the use of a sand of the nature of standard Ottawa sand is not permitted except in mixes 1:2 or richer.

The curves in Figure 5 are platted directly from the values given for the standard sieves in Table 3.

Chart for Design of Concrete Mixes

Fig. 6 is a nomographic chart for the design of concrete mixes. This chart takes account of the following four factors:

1. The mix (cement content).
2. The relative consistency.
3. The grading of aggregate (fineness modulus).
4. The compressive strength of concrete.

Given any three of these factors the chart enables us to solve for the fourth. This chart is, of course, based on the results of certain tests. For practical application these values must generally be reduced by certain factors, which will depend on the judgment of the designer. In order to furnish some basis for comparison, compression tests of 1:3 standard sand mortars from the cement used in these tests are given.

Suppose we consider the case of concrete for road construction. This is generally specified as a 1:1½:3 or a 1:2:3 mix, with aggregate graded up to 1½ in. These mixes are about the same as what have been termed a 1:4 mix, the exact equivalent depending on the particular size and grading of the fine and coarse aggregate. Assume that gravel aggregate will be used, graded to 1½ in. Table 3 shows that we may use a fineness modulus as high as 6.00 — .25 = 5.75. Knowing the sieve analysis and fineness modulus of both sizes of aggregate, apply the formula or Fig. 7 to determine the proportions of each aggregate which must be mixed to secure this value. Assume that the concrete will be mixed to a relative consistency of 1.10, which is of such plasticity as will give a slump of 5 to 6 in. in the test described above.* Place a straightedge in Fig. 6 on mix 1:4 and fineness modulus 5.75, and mark the point where it crosses the reference line for consistency; from this point project the line horizontally (as indicated in other examples) to relative consistency 1.10. It will be seen that this gives a compressive strength of 3,400 lb. per sq. in. at 28 days.

The effect of using other mixes, gradings or consistencies on the strength can be seen at once from the diagram. For instance, if the water were increased to a relative consistency of 1.25 (not nearly so wet as is frequently seen in road work) the strength will be reduced to 2,700 lb. per sq. in.—a reduction of over 20 per cent. If the mix were changed to 1:4½ and other factors the same as in the first example, the strength would be 3,200 lb. per sq. in. We should have to change the mix to as lean as 1:5¼ in order to secure the same reduction in strength as was found above for a change from 1.10 to 1.25 consistency.

By using the wetter of the two consistencies we secure concrete of the same strength as if we had used one-third less cement and the drier mix. In other words, increasing the mixing water 13% causes the same reduction in strength as if we should omit 33% of the cement. This example shows the reason for emphasizing the importance of proper control of mixing water in concrete.

This chart enables us to answer such questions as the following:

Which is the stronger, a 1:3 mortar or a 1:5 concrete mixture?

Assuming that concrete of the same plasticity is used, the relative strengths will depend, of course, on the grading of the aggregates and the mix. In one case we have assumed 1:3 mix with fineness modulus equal to 3.00. This will give a strength for normal consistency of 3,000 lb. per sq. in. The 1:5 mix (fineness modulus 5.70) gives a strength for normal consistency of about 3,300 lb. per sq. in. The strengths for other consistencies can be found by reading horizontally across the chart as indicated by the dotted lines.

Unfortunately, we now have no proper basis for absolute values for strength of concrete. This, of course, makes it necessary to refer to particular tests as in Fig. 6. This condition emphasizes the importance of working out a test of cement which will give us at once the concrete strength for given materials, mixes, etc. With the present method of testing cement it is impossible to do more than make a rough guess as to the strength of concrete from the results of briquet tests.

Quantity of Water Required for Concrete

The formulas given above (4 and 5) show the elements which make up the water-requirements of a concrete mix. Table 4 gives the quantity of water required for certain mixes and values of fineness modulus. Quantities are given in terms of gallons per sack of cement. In this table no allowance is made for the absorption of the aggregate and moisture in the aggregate. This table is of interest when we consider that it has been found that a given water-ratio corresponds to constant concrete strength regardless of the combination of mix, consistency or grading of aggregate which may be used, so long as we have a workable concrete.

Further Discussion of Concrete Mixes

The importance of the water-ratio on the strength of concrete will be shown in the following considerations:

One pint more water than necessary to produce a plastic concrete reduces the strength to the same extent as if we should omit 2 to 3 lb. of cement from a 1-bag batch.

*See footnote on page 7.

Our studies give us an entirely new conception of the function performed by the various constituent materials. The use of a coarse, well-graded aggregate results in no gain in strength unless we take advantage of the fact that the amount of water necessary to produce a plastic mix can thus be reduced. In a similar way we may say that the use of more cement in a batch does not produce any beneficial effect except from the fact that a plastic, workable mix can be produced with a lower water-ratio.

The reason a rich mixture gives a higher strength than a lean one is not that more cement is used, but because the concrete can be mixed (and usually is mixed) with a water-ratio which is relatively lower for the richer mixtures than for the lean ones. If advantage is not taken of the fact that in a rich mix relatively less water can be used, no benefit will be gained as compared with a leaner mix. In all this discussion the quantity of water is compared with the quantity of cement in the batch (cubic feet of water to 1 sack of cement) and not to the weight of dry materials or of the concrete as is generally done.

The mere use of richer mixes has encouraged a feeling of security, whereas in many instances nothing more has been accomplished than wasting a large quantity of cement, due to the use of an excess of mixing water. The universal acceptance of this false theory of concrete has exerted a most pernicious influence on the proper use of concrete materials and has proven to be an almost insurmountable barrier in the way of progress in the development of sound principles of concrete proportioning and construction.

Rich mixes and well-graded aggregates are just as essential as ever, but we now have a proper appreciation of the true function of the constituent materials in concrete and a more thorough understanding of the injurious effect of too much water. Rich mixes and well-graded aggregates are after all only a means to an end; that is, to produce a plastic, workable concrete with a minimum quantity of water as compared with the cement used. Workability of concrete mixes is of fundamental significance. This factor is the only limitation which prevents the reduction of cement and water in the batch to much lower limits than are now practicable.

The above considerations show that the water content is the most important element of a concrete mix, in that small variations in the water cause a much wider change in the strength than similar variations in the cement content or the size or grading of the aggregate. This shows the absurdity of our present practice in specifying definite gradings for aggregates and carefully proportioning the cement, then guessing at the water. It would be more correct to carefully measure the water and guess at the cement in the batch.

The grading of the aggregate may vary over a wide range without producing any effect on concrete strength, so long as the cement and water remain unchanged. The consistency of the concrete will be changed, but this will not affect the concrete strength if all mixes are plastic. The possibility of improving the strength of concrete by better grading of aggregates is small as compared with the advantages which may be reaped from using as dry a mix as can be properly placed. Table 4 shows the effect of water on the strength of concrete.

It is impracticable to lay down a general rule for the quantity of water which should be used in a concrete mix, since it was seen in the water formulas given above that the total water is governed by a large number of different factors. However, it is only the water which goes to the cement (that is, exclusive of absorbed water) which affects the concrete strength. The failure to recognize this fact has led to many erroneous conclusions from tests made to determine the relative merits of different aggregates.

Table 4 gives the quantity of water required for plastic mixes for certain assumed conditions of normal consistency of cement, absorption of aggregate, and relative consistency. Water is expressed in terms of gallons per sack of cement. In using this table the dependence of the value of fineness modulus which may be used on the size of aggregate and the mix, referred to in Table 3, should not be overlooked.

Without regard to the actual quantity of mixing water, the following rule is a safe one to follow: *Use the smallest quantity of mixing water that will produce a plastic or workable concrete.* The importance of any method of mixing, handling, placing and finishing concrete which will enable the builder to reduce the water content of the concrete to a minimum is at once apparent.

Table 1

METHOD OF CALCULATING FINENESS MODULUS OF AGGREGATES

The *sieves* used are commonly known as the Tyler standard sieves. Each sieve has a *clear opening* just double that of the preceding one.

The *sieve analysis* may be expressed in terms of volume or weight.

The *fineness modulus* of an aggregate is the sum of the percentages given by the sieve analysis, divided by 100.

Sieve Size	Size of Square Opening		Sieve Analysis of Aggregates — Per Cent of Sample Coarser than a Given Sieve						
			Sand			Pebbles			Concrete
	in.	mm.	Fine (A)	Medium (B)	Coarse (C)	Fine (D)	Medium (E)	Coarse (F)	Aggregate (G)**
100-mesh	.0058	.147	82	91	97	100	100	100	98
48-mesh*.....	.0116	.295	52	70	81	100	100	100	92
28-mesh*.....	.0232	.59	20	46	63	100	100	100	86
14-mesh*.....	.046	1.17	0	24	44	100	100	100	81
8-mesh	.093	2.36	0	10	25	100	100	100	78
4-mesh	.185	4.70	0	0	0	86	95	100	71
⅜-in.	.37	9.4	0	0	0	51	66	86	49
¾-in.	.75	18.8	0	0	0	9	25	50	19
1½-in.	1.5	38.1	0	0	0	0	0	0	0
Fineness Modulus.....			1.54	2.41	3.10	6.46	6.86	7.36	5.74

*(Note added at fifth printing, October, 1922.) The No. 48, 28, and 14-mesh sieves give the same separation as the No. 50, 30, and 16 now used in the "Tentative Method of Test for Sieve Analysis of Aggregates for Concrete" of the American Society for Testing Materials. The No. 50, 30, and 16 sieves are now used in all our tests.

**Concrete aggregate "G" is made up of 25% of sand "B" mixed with 75% of pebbles "E." Equivalent gradings would be secured by mixing 33% sand "B" with 67% coarse pebbles "F"; 28% "A" with 72% "F," etc. The proportion coarser than a given sieve is made up by the addition of these percentages of the corresponding size of the constituent materials.

Table 2

EFFECT OF GRADING OF AGGREGATES ON THE STRENGTH OF CONCRETE

Compression tests of 6 by 12-in. concrete cylinders.

Mix 1:5 by volume; age at test, 28 days; stored in damp sand; tested damp.

Aggregates—sand and pebbles from Elgin, Ill. Aggregates were screened to different sizes and recombined to conform to predetermined sieve analyses.

The aggregates were made up in such a manner as to give the widest variations in the grading of the particles. All gradings had one common property, in that the *fineness modulus* was exactly the same—m = 6.04. The fineness modulus of the aggregate is the sum of the percentages in the sieve analysis, divided by 100.

The same quantity of water was used in all specimens of a given consistency. The 110% consistency contains 10% more water than the 100%.

Each specimen was made from a separate batch.

Each value in the strength tests is the average from 5 tests made on different days. (From Series 78.)

Ref.	Sieve Analysis of Aggregate Per Cent Coarser than Each Sieve										Fineness Modulus of Aggregate	Surface Area of Aggregate sq. in. per lb. of Aggregate	per g. of Cement	Compressive Strength of Concrete at 28 days (lb. per sq. in.) 100% Consistency	110% Consistency
No.	100	48	28	14	8	4	⅜	¾	1¼	1½ 2					
40	99	98	95	90	81	68	49	24	0		6.04	602	8.8	3,300	2,890
259	99	98	96	92	84	67	46	22	0		6.04	569	8.2	2,950	2,650
260	98	97	93	88	80	67	52	29	0		6.04	764	11.4	3,120	2,760
261	97	94	91	85	77	67	58	35	0		6.04	999	15.2	3,140	2,790
262	95	92	87	82	75	67	67	39	0		6.04	1,292	20.1	3,100	2,800
263	95	90	84	78	73	67	62	55	0		6.04	1,451	23.0	2,830	2,740
264	95	89	82	75	67	67	67	62	0		6.04	1,565	25.2	2,680	2,580
265	100	97	91	79	72	67	58	40	0		6.04	761	11.9	3,070	2,690
266	100	97	93	88	83	67	50	27	7	0	6.04	616	9.0	3,080	2,790
267	99	97	94	86	77	67	47	27	16	— 0	6.04	709	10.5	3,150	2,710
268	98	95	90	83	83	83	50	22	0		6.04	834	12.6	3,080	2,500
269	98	94	90	86	83	80	55	18	0		6.04	898	13.3	3,050	2,550
270	96	90	80	80	80	80	60	39	0		6.04	1,391	21.5	2,970	2,550
271	100	96	92	87	81	75	50	23	0		6.04	672	10.0	2,930	2,710
272	95	91	87	82	77	73	59	40	0		6.04	1,315	20.2	3,000	2,580
273	99	95	88	80	76	73	61	32	0		6.04	911	13.9	2,950	2,740
274	90	85	81	78	75	73	66	56	0		6.04	1,992	31.3	2,680	2,440
275	100	93	82	73	73	73	63	47	0		6.04	1,076	16.7	2,820	2,620
276	100	100	100	92	81	60	45	26	0		6.04	390	5.6	3,040	2,780
277	100	98	95	90	80	60	50	31	0		6.04	557	8.3	2,900	2,770
278	100	99	96	92	84	55	50	28	0		6.04	483	7.0	2,940	2,750
279	100	99	96	91	80	50	50	38	0		6.04	514	7.6	3,080	2,750
280	98	84	84	84	84	57	57	57	0		6.04	1,276	19.7	3,000	2,780
281	99	98	91	86	80	76	38	38	0		6.04	701	10.4	2,940	2,700
282	99	98	91	86	80	76	46	30	0		6.04	697	10.2	3,020	2,660
283	99	98	91	86	80	76	61	15	0		6.04	689	10.1	2,930	2,670
284	99	98	91	85	80	76	67	8	0		6.04	685	9.9	2,970	2,630
Average											6.04	904	13.8	2,990	2,690
Minimum Value											....	390	5.6	2,680	2,440
Maximum Value											....	1,992	31.3	3,300	2,890
Mean Variation from Average—per cent											....	34.4	37.2	3.41	3.04

Table 3

MAXIMUM PERMISSIBLE VALUES OF FINENESS MODULUS OF AGGREGATES

For *mixes* other than those given in the table, use the values for the next leaner mix.

For *maximum sizes* of aggregate other than those given in the table, use the values for the next smaller size.

Fine aggregate includes all material finer than No. 4 sieve; *coarse aggregate* includes all material coarser than the No. 4 sieve. *Mortar* is a mixture of cement, water and fine aggregate.

This table is based on the requirements for *sand-and-pebble* or *gravel* aggregate composed of approximately spherical particles, in ordinary uses of concrete in reinforced concrete structures. For other materials and in other classes of work the maximum permissible values of fineness modulus for an aggregate of a given size is subject to the following corrections:

(1) If *crushed stone* or *slag* is used as coarse aggregate, *reduce* values in table by 0.25. For crushed material consisting of unusually flat or elongated particles, *reduce* values by 0.40.

(2) For *pebbles* consisting of *flat particles, reduce* values by 0.25.

(3) If *stone screenings* are used as fine aggregate, *reduce* values by 0.25.

(4) For the top course in *concrete roads, reduce* the values by 0.25. If finishing is done by *mechanical means,* this reduction need not be made.

(5) In work of *massive proportions,* such that the smallest dimension is larger than 10 times the maximum size of the coarse aggregate, *additions may be made* to the values in the table as follows: for ¾-in. aggregate 0.10; for 1½-in. 0.20; for 3-in. 0.30; for 6-in. 0.40.

Sand with fineness modulus lower than 1.50 is undesirable as a fine aggregate in ordinary concrete mixes. Natural sands of such fineness are seldom found.

Sand or screenings used for fine aggregate in concrete must not have a higher fineness modulus than that permitted for mortars of the same mix. Mortar mixes are covered by the table and by (3) above.

Crushed stone mixed with both finer sand and coarser pebbles requires no reduction in fineness modulus provided the quantity of crushed stone is less than 30% of the total volume of the aggregate.

The values from this table are platted in Fig. 3.

Mix	Size of Aggregate													
Cem.-Agg.	0-28	0-14	0-8	0-4	0-3*	0-⅜	0-½*	0-¾	0-1 in.*	0-1½	0-2.1*	0-3 in.	0-4½*	0-6 in.
1-9.....	1.30	1.85	2.45	3.05	3.45	3.85	4.25	4.65	5.00	5.40	5.80	6.25	6.65	7.05
1-7.....	1.40	1.95	2.55	3.20	3.55	3.95	4.35	4.75	5.15	5.55	5.95	6.40	6.80	7.20
1-6.....	1.50	2.05	2.65	3.30	3.65	4.05	4.45	4.85	5.25	5.65	6.05	6.50	6.90	7.30
1-5.....	1.60	2.15	2.75	3.45	3.80	4.20	4.60	5.00	5.40	5.80	6.20	6.60	7.00	7.45
1-4.....	1.70	2.30	2.90	3.60	4.00	4.40	4.80	5.20	5.60	6.00	6.40	6.85	7.25	7.65
1-3.....	1.85	2.50	3.10	3.90	4.30	4.70	5.10	5.50	5.90	6.30	6.70	7.15	7.55	8.00
1-2.....	2.00	2.70	3.40	4.20	4.60	5.05	5.45	5.90	6.30	6.70	7.10	7.55	7.95	8.40

*Considered as "half-size" sieves; not used in computing fineness modulus.

Table 4

QUANTITY OF MIXING WATER REQUIRED FOR CONCRETE

Calculated by formula: $x = R\left[\frac{3}{2}p + \frac{.30n}{1.26^m}\right] + (a-c)\,n$

Where x = Water required—ratio to volume of cement in batch (water-ratio).

R = Relative consistency, or "workability factor." Where R = 1.00 the concrete is said to be of "normal consistency."

p = Normal consistency of cement by weight (assume p = 0.23).

m = Fineness modulus of aggregate.

n = Volume of mixed aggregate to one volume of cement.

a = Absorption of aggregate, ratio of water absorbed to volume of aggregate.

c = Moisture in aggregate, ratio of water contained to volume of aggregate.

(a — c) = Net absorption of aggregate by volume.

No allowance is made for the absorption of the aggregate and moisture in the aggregate. In other words, no allowance is made for the net absorption (a — c). This may be determined by tests on the aggregate in the field.

To determine the number of gallons of water per sack of cement, multiply the water-ratio (x) by 7.48.

A relative consistency of 1.00 (normal consistency) requires the use of such a quantity of mixing water as will cause a slump of ½ to 1 in.* in a freshly molded 6 by 12-in. cylinder of about 1:4 mix upon withdrawing the form by a steady, upward pull. This consistency is somewhat dry for most concrete work, but can be used where light tamping is practicable.

A relative consistency of 1.10 (10% more water than required for normal consistency) represents about the driest concrete which can be satisfactorily used in concrete road construction. Under the conditions mentioned above, this consistency will give a slump of about 5 to 6 in.*

A relative consistency of 1.25 represents about the wettest consistency which should be used in reinforced concrete building construction. Under the conditions mentioned above, this consistency will give a slump of about 8 to 9 in.*

For mixes and fineness moduli, other than those given in the table, approximate values may be determined by interpolation. For specific cases use the formula.

Mix Cem.-Agg. by Volume	Gallons of Water per Sack of Cement Using Aggregates of Different Fineness Moduli											
	1.50	2.00	2.50	3.00	3.50	4.00	4.50	5.00	5.50	6.00	6.50	7.00
Relative Consistency — (R) = 1.00												
1-9	16.8	15.3	13.9	12.7	11.6	10.6	9.7	9.0	8.2	7.6	7.1	6.6
1-7	13.7	12.5	11.4	10.4	9.6	8.8	8.1	7.6	7.0	6.5	6.1	5.7
1-6	12.1	11.1	10.1	9.3	8.6	7.9	7.3	6.8	6.4	6.0	5.6	5.3
1-5	10.5	9.6	8.9	8.2	7.6	7.0	6.6	6.1	5.7	5.4	5.1	4.8
1-4	9.0	8.2	7.6	7.1	6.6	6.2	5.8	5.4	5.1	4.8	4.6	4.4
1-3	7.3	6.8	6.4	6.0	5.6	5.3	5.0	4.7	4.5	4.3	4.1	3.9
1-2	5.7	5.4	5.1	4.8	4.6	4.4	4.2	4.0	3.8	3.7	3.6	3.5
Relative Consistency — (R) = 1.10												
1-9	18.5	16.8	15.3	14.0	12.8	11.6	10.7	9.9	9.0	8.4	7.8	7.3
1-7	15.1	13.7	12.5	11.4	10.6	9.7	8.9	8.4	7.7	7.2	6.7	6.3
1-6	13.3	12.2	11.1	10.2	9.5	8.7	8.0	7.5	7.0	6.6	6.2	5.8
1-5	11.5	10.6	9.8	9.0	8.4	7.7	7.3	6.7	6.3	5.9	5.6	5.3
1-4	9.9	9.0	8.4	7.8	7.3	6.8	6.4	5.9	5.6	5.3	5.1	4.8
1-3	8.0	7.5	7.0	6.6	6.2	5.8	5.5	5.2	5.0	4.7	4.5	4.3
1-2	6.3	5.9	5.6	5.3	5.1	4.8	4.6	4.4	4.2	4.1	4.0	3.8
Relative Consistency — (R) = 1.25												
1-9	21.0	19.1	17.4	15.9	14.5	13.3	12.1	11.3	10.2	9.5	8.9	8.2
1-7	17.1	15.6	14.3	13.0	12.0	11.0	10.1	9.5	8.8	8.1	7.6	7.1
1-6	15.1	13.9	12.6	11.6	10.8	9.9	9.1	8.5	8.0	7.5	7.0	6.6
1-5	13.1	12.0	11.1	10.3	9.5	8.8	8.2	7.6	7.1	6.8	6.4	6.0
1-4	11.2	10.3	9.5	8.9	8.2	7.8	7.2	6.8	6.4	6.0	5.8	5.5
1-3	9.1	8.5	8.0	7.5	7.0	6.6	6.3	5.9	5.6	5.4	5.1	4.9
1-2	7.1	6.7	6.4	6.0	5.8	5.5	5.3	5.0	4.8	4.6	4.5	4.4

*See footnote on page 7.

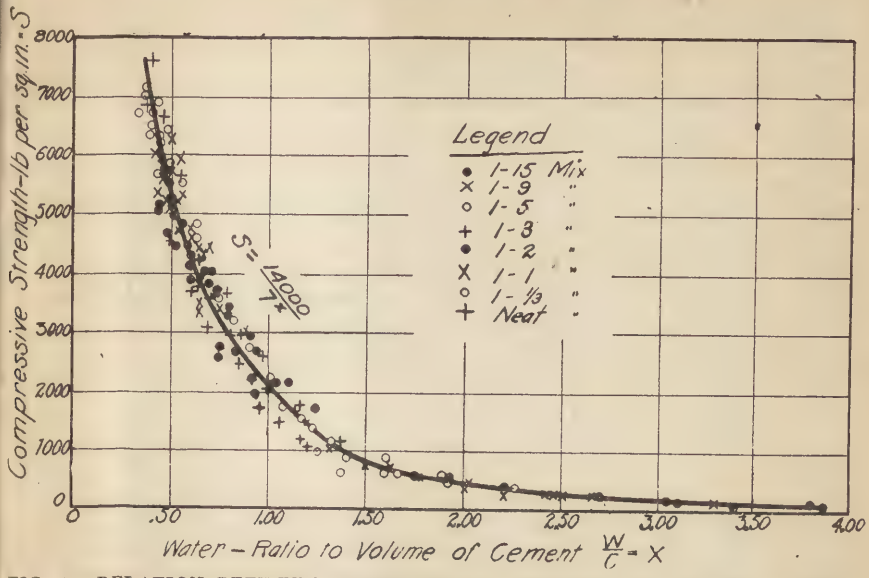


FIG. 1. RELATION BETWEEN STRENGTH OF CONCRETE AND WATER CONTENT
Twenty-eight-day compression tests of 6 by 12-inch cylinders. (Series 83.)

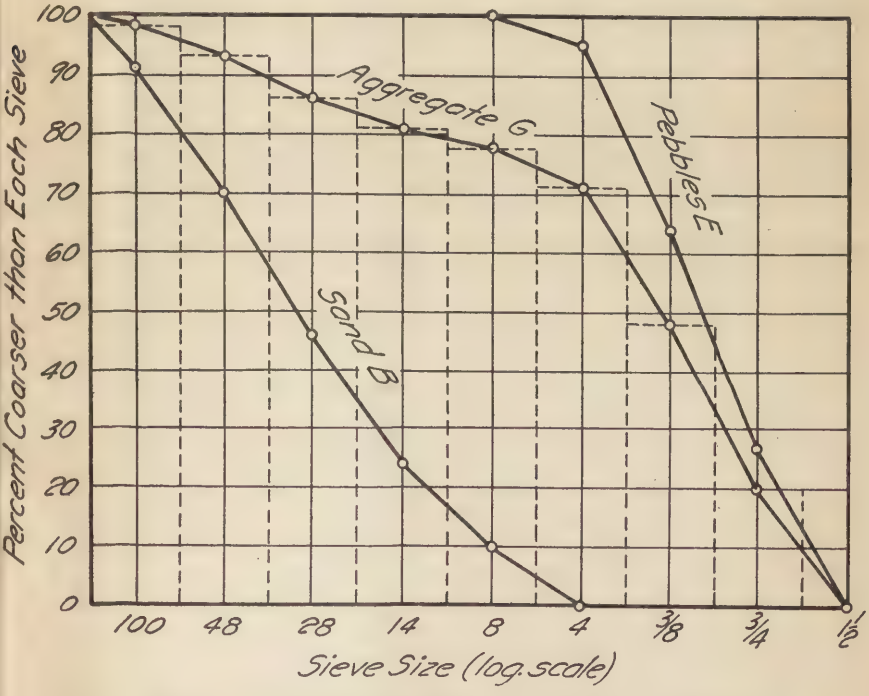
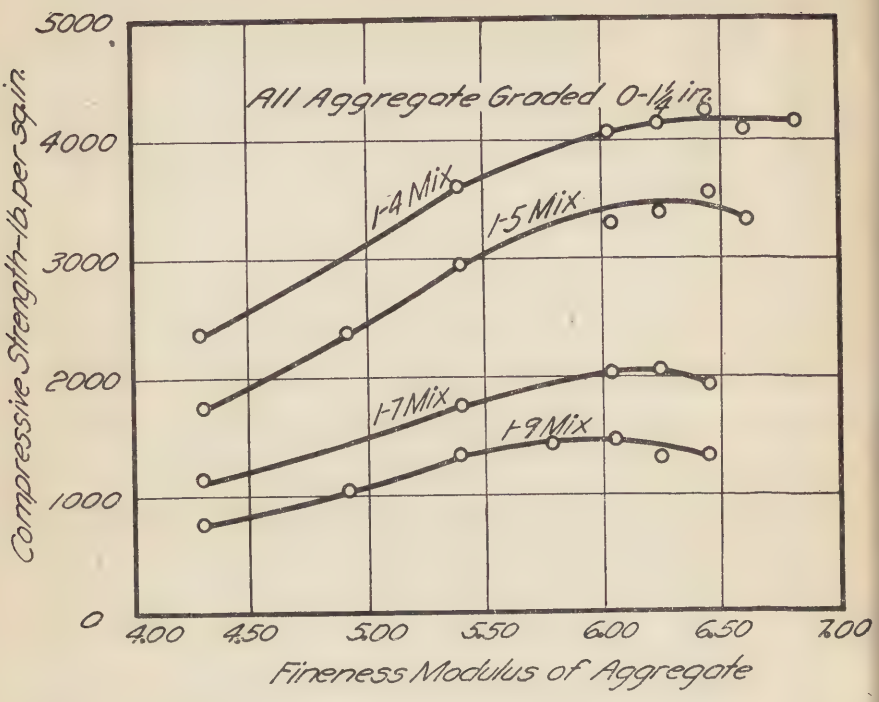


FIG. 2. METHOD OF PLOTTING SIEVE ANALYSIS OF AGGREGATES
Sieve analysis curves for aggregates B, E and G in Table 1.

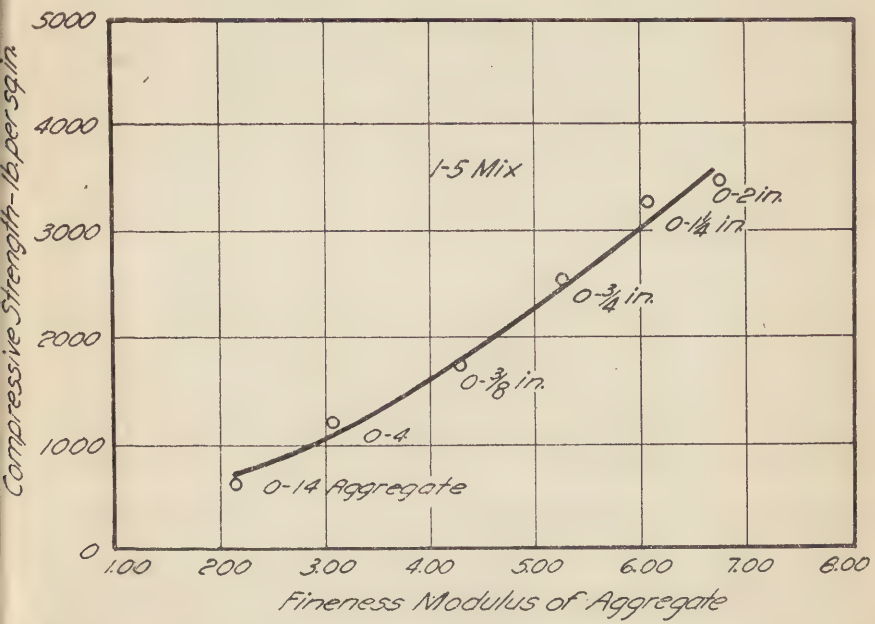


Sand and pebble aggregate graded 0-1¼ inch; 28-day compression tests of 6 by 12-inch cylinders. (Series 78.)

The sieve analyses of the aggregates in Fig. 3 are given below:

Range in Size	Fineness Modulus	Per Cent Coarser than Each Sieve									
		100	48	28	14	8	4	⅜	¾	1½	2
0-1¼	4.30	89	82	72	62	51	38	25	11	0	..
"	4.93	95	89	82	73	61	47	32	14	0	..
"	5.40	98	94	88	80	69	55	38	18	0	..
"	6.04	99	98	95	90	81	68	49	24	0	..
"	6.25	100	99	97	92	85	72	53	27	0	..
"	6.45	100	99	98	95	88	77	58	30	0	..
"	6.60	100	100	99	96	91	80	62	32	0	..
"	6.82	100	100	99	98	94	86	68	37	0	..

FIG. 3. RELATION BETWEEN FINENESS MODULUS OF AGGREGATE AND STRENGTH OF CONCRETE



Twenty-eight-day compression tests of 6 by 12-inch cylinders. (Series 78.) Sand and pebble aggregate graded to sizes shown. The contrast between the relation shown by these tests and those in Fig. 3 should be noted.

The sieve analyses of the aggregates in Fig. 4 are given below:

Range in Size	Fineness Modulus	Per Cent Coarser than Each Sieve									
		100	48	28	14	8	4	⅜	¾	1½	2
0-14	2.16	95	84	37	0	..	..	..	..	..	..
0- 4	3.06	96	90	62	40	18	0	..	..	..	..
0- ⅜	4.26	96	91	83	71	54	31	0	..	..	..
0- ¾	5.24	98	96	91	83	71	54	31	0	..	..
0- 1¼	6.04	99	98	95	90	81	68	49	24	0	..
0- 2	6.72	100	99	97	94	87	77	62	42	14	0

FIG. 4. RELATION BETWEEN FINENESS MODULUS OF AGGREGATE AND STRENGTH OF CONCRETE

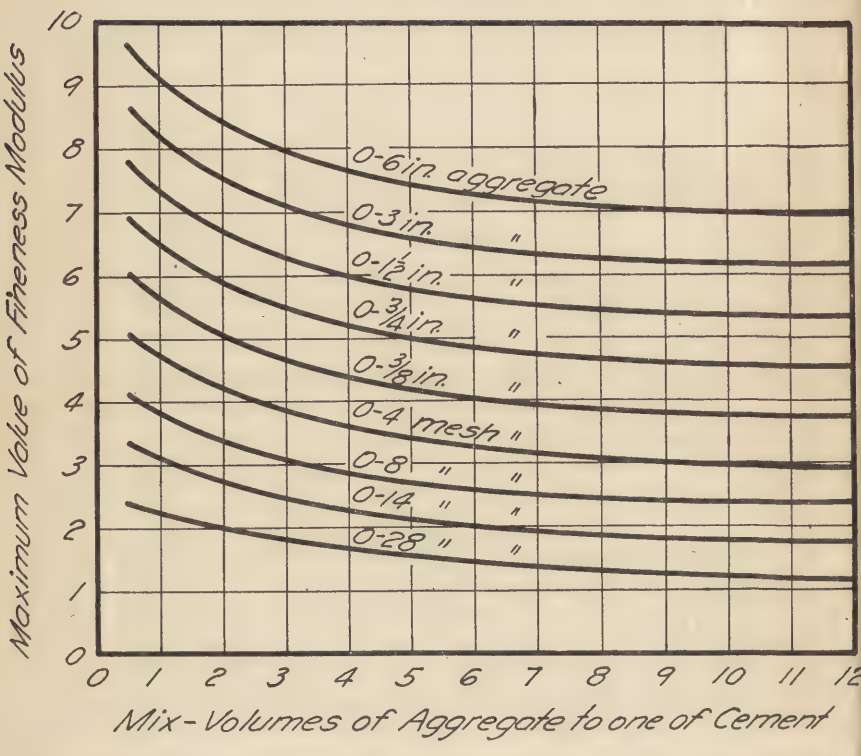
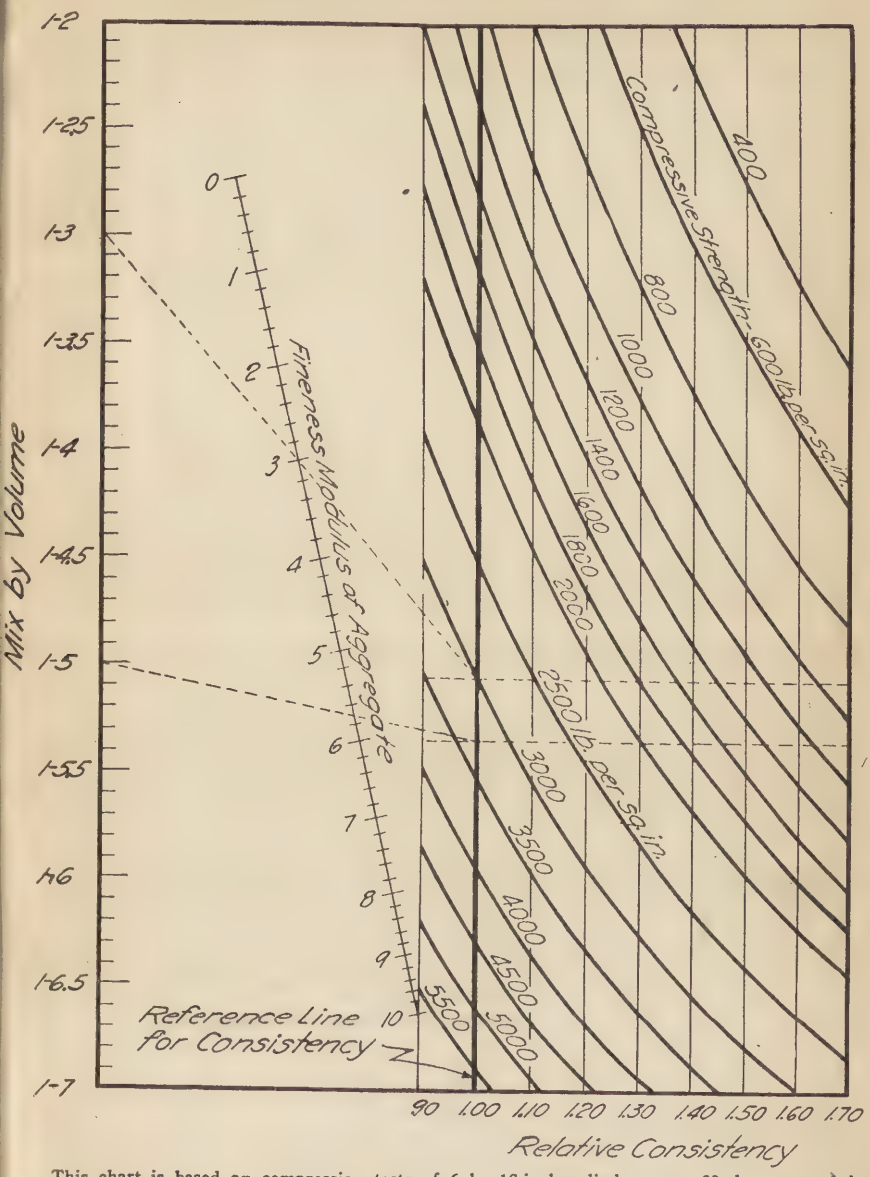


FIG. 5. MAXIMUM PERMISSIBLE VALUES OF FINENESS MODULUS OF AGGREGATE

Graphical reproduction of Table 3. These curves are based on the requirements of sand and pebble aggregate. For crushed stone aggregate the values must be reduced as noted in the table.



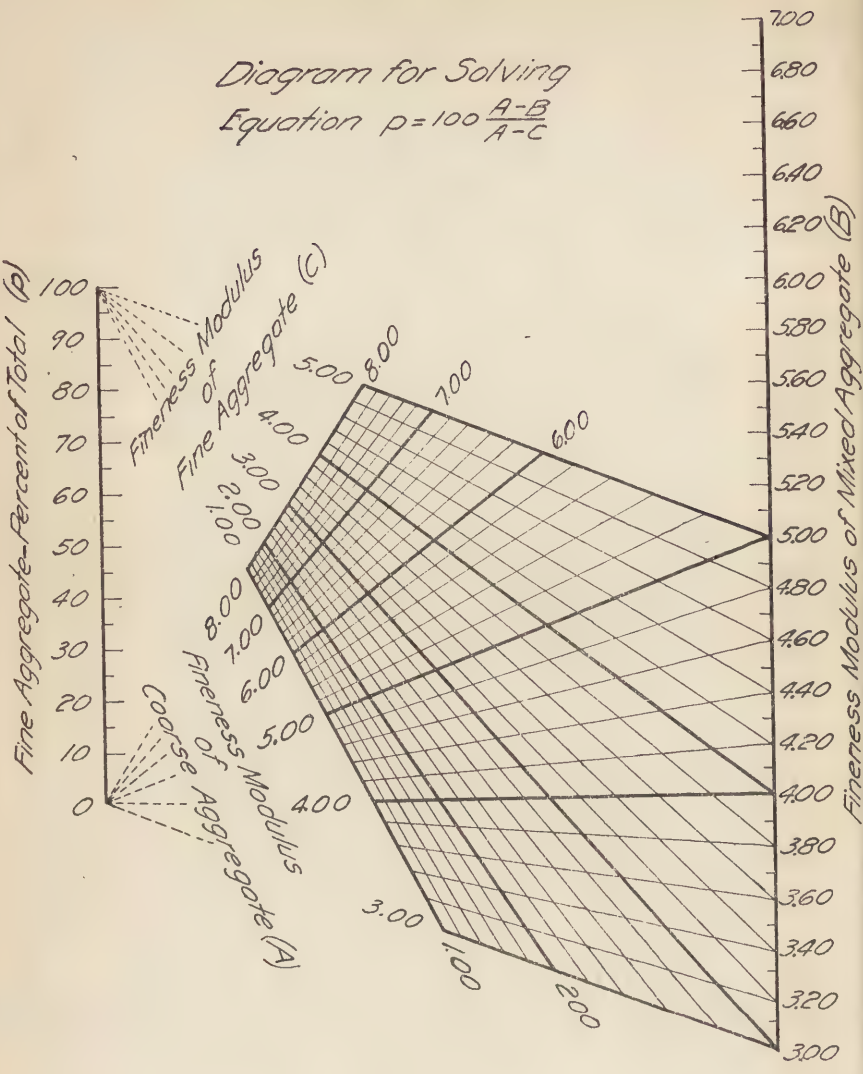
This chart is based on compression tests of 6 by 12-inch cylinders; age 28 days; stored in damp sand.

The cement used gave compressive strengths in 1-3 standard sand mortar as follows, when tested in the form of 2 by 4-inch cylinders:

Age	Lb. per Sq. In.
7 days	1,900
28 days	3,200
3 months	4,200
1 year	4,300

See Table 3 for maximum permissible values of fineness modulus of aggregates for concretes of different mixes.

FIG. 6. DIAGRAM FOR THE DESIGN OF CONCRETE MIXTURES



Based on equation $p = 100 \frac{A-B}{A-C}$

where p = percentage of fine aggregate in total mixture.
A = fineness modulus of coarse aggregate.
B = fineness modulus of total aggregate.
C = fineness modulus of fine aggregate.

FIG. 7. DIAGRAM FOR DETERMINING QUANTITY OF SAND REQUIRED IN CONCRETE MIXES

Bulletin 2

Structural Materials Research Laboratory
Lewis Institute
Chicago

Effect of Curing Condition on the Wear and Strength of Concrete

By

DUFF A. ABRAMS
Professor in Charge of Laboratory

(Authorized Reprint from the Proceedings of the American Railway Engineering Association, Vol. 20, 1919)

Published by the
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Third Printing, September, 1922

FOREWORD

This paper was first published as a part of the Report of the Committee on Masonry of the American Railway Engineering Association (Proceedings, Vol. 20, 1919). It was reprinted as Bulletin 2 of this Laboratory in May, 1919. A second printing was necessary in December, 1920. At that time a few minor errors were corrected and the bibliography was brought up to date by the addition of a number of references which did not appear in the original report.

A third printing is now necessary. A few footnotes have been added which show departures of present practice from that followed in the tests. The bibliography has been again revised.

Acknowledgment is made to the American Railway Engineering Association for permission to reprint this paper in bulletin form.

EFFECT OF CURING CONDITION ON THE WEAR AND STRENGTH OF CONCRETE

By Duff A. Abrams.

Introduction.

The necessity for careful restriction on the quantity of mixing water used in concrete, and the importance of proper curing conditions during the period of setting and hardening are not generally appreciated by engineers and contractors doing concrete work. In view of the widespread use of concrete in the construction of pavements, floors, loading platforms, and in other places requiring high strength and resistance to abrasion, it seemed desirable to carry out an experimental study which would bring out the effect of water content and curing conditions on the compressive strength and the wearing resistance of concrete, and the relation between these two properties.

These tests were made as a part of the experimental studies of the properties of concrete and concrete materials, being carried out through the cooperation of Lewis Institute and the Portland Cement Association at the Structural Materials Research Laboratory.

This series comprised compression tests of 120 6 by 12-in. cylinders and wear tests on 300 blocks, 8 in. square and 5 in. in thickness. A 1:4 mix was used throughout, that is, 1 volume cement and 4 volumes mixed aggregate. This mix is about the same as the 1 : 1½ : 3 or 1 : 2 : 3 mixes generally used for concrete which is to withstand high stresses or to form the wearing surface of pavements. Most of the tests were made on sand and pebble aggregates. One group was repeated with crushed limestone as coarse aggregate.

Concrete of six different consistencies was used, each being stored under four different conditions:

(1) Damp sand 4 months (120 days), tested damp,
(2) Damp sand 21 days, air 99 days,
(3) Damp sand 3 days, air 117 days,
(4) Air of laboratory for entire curing period of 4 months.

Parallel tests were made throughout on compression and wear. All tests were made at the age of 4 months.

The wear blocks were tested in the Talbot-Jones rattler by the same methods that were used in other tests carried out in this Laboratory.*

Acknowledgment is due to the Chicago Gravel Company, Chicago, for their courtesy in furnishing the sand and pebble aggregate used in these tests, and to Dolese & Shepard, Chicago, for the crushed limestone.

*See "A Method of Making Wear Tests of Concrete," by D. A. Abrams, Proc. Am. Soc. Testing Mat., Part II, 1916; also "Effect of Time of Mixing on the Strength and Wear of Concrete," by D. A. Abrams, Proc. Am. Concrete Ins., 1918.

MATERIALS.

The portland cement used in these tests consisted of a mixture of equal parts of four brands purchased in the Chicago market. The brands were thoroughly mixed by placing one sack of each in a concrete mixer and running for about one minute. Complete tests of the cement are given in Table 1.

TABLE 1—TESTS OF CEMENT.

The cement consisted of a mixture of equal parts of four brands purchased on the Chicago market (Lot No. 3705).

All tests made in accordance with Standard Specifications and Tests for Portland Cement of the American Society for Testing Materials.

Miscellaneous Tests.

Fineness Residue on 200 Sieve	Normal Consistency Per Cent by Weight	Time of Setting				Soundness Test (over Boiling Water)
		Vicat Needle		Gillmore Needle		
		Initial	Final	Initial	Final	
		h. m.	h. m.	h. m.	h. m.	
20.4	23.0	4:25	8:05	5:10	8:45	O.K.

Mortar Strength Tests.

1:3 standard sand mortar.

Mixing Water Per Cent	Tensile Strength of Briquets lb. per sq. in.						Compressive Strength of 2 by 4-in. Cylinders lb. per sq. in.					
	7 da.	28 da.	3 mo.	6 mo.	1 yr.	2 yr.	7 da.	28 da.	3 mo.	6 mo.	1 yr.	2 yr.
10.3	266	367	464	431	415	357	2080	3800	4240	5130	5060	4600

The aggregates consisted of sand and pebbles from the Chicago Gravel Company's plant near Elgin, Ill., and crushed limestone from Dolese & Shepard Company's quarry. Before using, the sand was screened through a No. 4 sieve. All material coarser than this size was rejected. The sand was used without further screening, but care was taken to see that the material in the bin was thoroughly mixed so that it was uniform throughout the series. Pebbles and crushed limestone were screened to three different sizes (No. 4-⅜, ⅜-¾, and ¾-1¼ in.) and recombined in definite proportions for each batch, as shown by the sieve analyses in Table 2.

The mixing and curing water was from the city water supply obtained from Lake Michigan.

The weights per cubic foot of aggregates were determined by means of machined, cast-iron measures having capacities of ⅛ and ½ cu. ft. The ⅛ cu. ft. measure was used for the sand and the ½ cu. ft. for the coarse aggregates and the mixed aggregates. The inside diameter of each measure is equal to the depth. The test was made by filling the measure about one-third full and puddling with a ⅝-in. steel bar pointed at the lower end. Filling and puddling were continued in like manner until the measure was full. After striking off with a straightedge the

weight was determined. This is the method recommended by Committee C-9 on Concrete of the American Society for Testing Materials, but the method has not yet been standardized by the Society.*

TABLE 2—SIEVE ANALYSIS OF AGGREGATES.

Sieves manufactured by the W. S. Tyler Company, Cleveland, Ohio.

Sieve Number or Size	Size of Clear Opening inches	Per Cent by Weight Coarser than Each Sieve				
		Sand	Pebbles	Crushed Lime-stone	Sand and Pebbles	Sand and Limestone
100	.0058	98	100	100	99	99
48*	.0116	90	100	100	96	96
28*	.023	60	100	100	84	84
14*	.046	42	100	100	77	77
8	.093	22	100	100	69	69
4	.185	0	100	100	60	60
⅜	.37	.....	84	84	50	50
¾	.75	.....	50	50	30	30
1¼	1.25	.....	0	0	0	0

*(Note added at Third Printing, September, 1922). The No. 48, 28, and 14-mesh sieves give the same separation as the No. 50, 30, and 16 now used in the "Tentative Method of Test for Sieve Analysis of Aggregates for Concrete" of the American Society for Testing Materials. The No. 50, 30 and 16 sieves are now used in all our tests.

TABLE 3—MISCELLANEOUS TESTS OF AGGREGATES.

Test	Sand	Pebbles	Crushed Lime-stone	Sand and Pebbles	Sand and Limestone
Unit Weight of Dry Aggregate lb. per cu. ft.	115.5	112.5	99.5	131.0	123.0
Absorption of Aggregate*					
Per cent by volume.....	2.3	2.2	1.6	.....	.....
Per cent by weight.....	1.3	1.3	1.0	.....	.....
Abrasion Test§					
Loss in weight—per cent					
Standard method.....	.....	2.3	5.2	.....	.....
Rea's method.....	.....	8.8	12.3	.....	.....

*After immersion in water at room temperature for 3 hr.

§Abrasion tests were made in the Deval abrasion testing machine. In the standard method a sample of 50 pieces weighing 5000 g. was placed in the test chamber and run for 10,000 revolutions. Rea's method was first used by A. S. Rea, of the Ohio State Highway Department, Columbus. It consists in using a 5000-g. sample, made up of 2500 g. of aggregate ½ to ¾ in. in size and 2500 g. of aggregate ¾ to 1½ in. In addition to the aggregate six 1⅞ in. cast-iron balls were placed in the test chamber as an abrasive charge. The entire sample was run for 10,000 revolutions. It will be seen that Rea's method is much more severe than the standard method.

The absorption of the aggregate was determined as follows:

The sand was dried to constant weight and cooled to room temperature in a desiccator. A 500-g. sample was placed in a 500-cc. volumetric flask and the volume of water necessary to fill to mark carefully measured. At frequent intervals the flask was filled to mark. The zero volume was obtained in the same manner, except that the sand was coated with kerosene to prevent absorption of water. This is an adaptation of Rea's method for determining specific gravity of fine aggregates.**

*(Note added at Third Printing, September, 1922). This method is now standard under the title "Standard Method of Test for Unit Weight of Aggregate for Concrete"; Serial Designation C 20-21.

**See "Apparent Specific Gravity of Non-Homogeneous Fine Aggregates," by A. S. Rea, Proc. Am. Soc. Testing Mat., Part II, 1917.

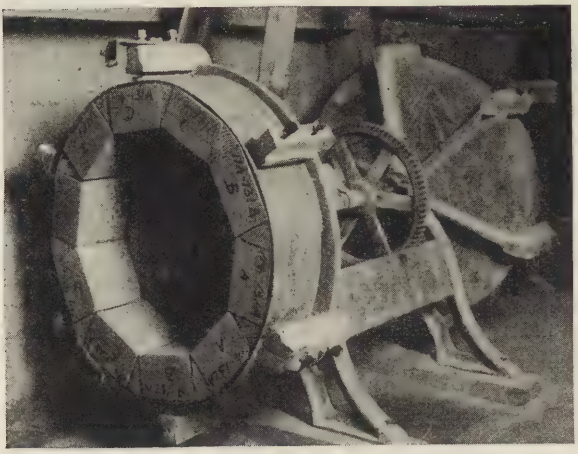


FIG. 1—TALBOT-JONES RATTLER WITH CONCRETE WEAR BLOCKS IN PLACE.
Wear tests were made on blocks 8 in. square, 5 in. thick.

The coarse aggregate was dried to constant weight, cooled to room temperature and weighed, then immersed in water at room temperature. At frequent intervals it was removed from the water, quickly surface-dried with a towel and weighed. Our experience with these methods indicates that the absorption at about 3 hours gives the best results in estimating the quantity of water necessary for concrete mixes.

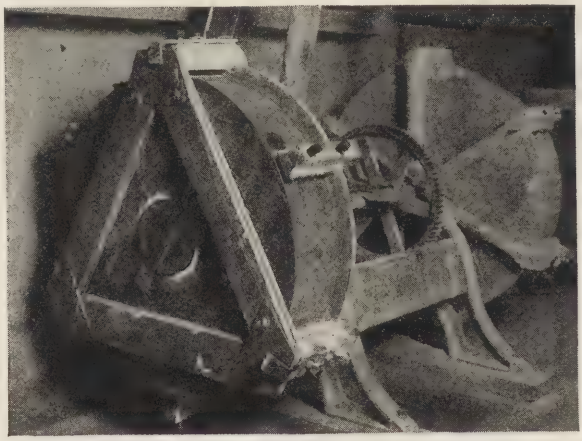


FIG. 2—TALBOT-JONES RATTLER WITH HEAD CLOSED READY FOR TEST.
The machine was operated for 1800 revolutions at 30 r. p. m.
The abrasive charge consisted of 200 lb. of cast-iron balls.

PROPORTIONING AND MIXING CONCRETE.

In all the tests included in this report the concrete consisted of a 1:4 mix by volume; that is, 1 volume of cement to 4 volumes of aggregate mixed as used considering 94 lbs. of cement as 1 cu. ft. This mix is equivalent to the 1:1½:3 or 1:2:3 mixes generally used for one-course concrete road construction. The exact equivalent of our 1:4 mix when expressed in the customary manner will depend on the size and grading of the aggregate.

The concrete was mixed by hand in the manner regularly followed in making such tests in this Laboratory. Each specimen was made from a separate batch of about ⅙ cu. ft., which was proportioned separately

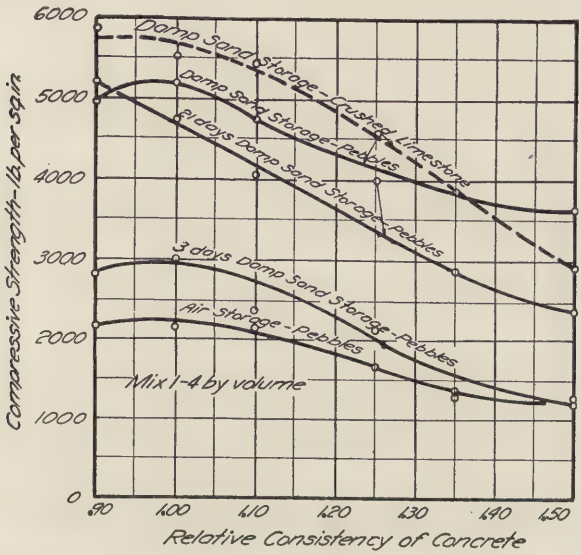


FIG. 3—EFFECT OF QUANTITY OF MIXING WATER ON THE STRENGTH OF CONCRETE.

Compression tests of 6 by 12-in. cylinders at age of 4 months. Each value is the average of four tests made on two different days. Same data as in Fig. 5.

and mixed with a bricklayer's trowel in a shallow metal pan. This method leaves no uncertainty as to the exact quantities of materials in each specimen.

The term "consistency" as used in this report refers to the plasticity of the concrete; that is, the relative and not the actual quantity of mixing water. It has been found convenient to express the quantity of water used in the concrete in terms of the volume of cement. This so-called water-ratio has been shown to be the best criterion of the strength of the concrete.

The consistency which we have called "normal" (relative consistency = 1.00) is of such a plasticity that a 6 by 12-in. cylinder* of 1:4 concrete will "slump" ½ to 1 in. upon removal of the metal form by a steady, upward pull immediately after molding the specimen. Concrete of relative consistency of 1.10 will show a slump of 5 to 6 in.; 1.25, a slump of 8 to 9 in.

TEST PIECES.

This report covers compression tests of 6 by 12-in. concrete cylinders and wear tests on concrete blocks 8 in. square and 5 in. in thickness.

The 6 by 12-in. cylinders were molded in metal forms made of 12-in. lengths of 6-in. inside diameter cold drawn steel tubing, which had been split along one element by means of a thin slotter. The form was closed by a circumferential band. Each form stood on a machined, cast-iron

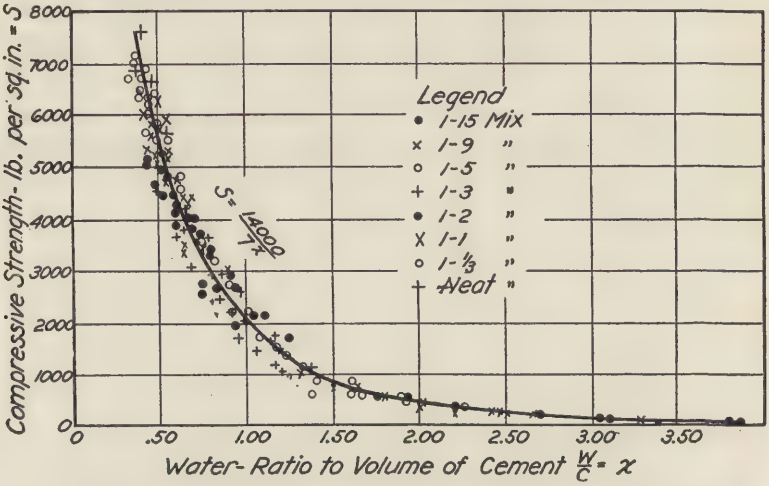


FIG. 4—EFFECT OF QUANTITY OF MIXING WATER ON THE STRENGTH OF CONCRETE.

Compression tests of 6 by 12-in. cylinders at age of 28 days. Each value is the average from five tests. Details of these tests are not given in this report.

base plate. A thin sheet of paraffined tissue paper was placed between the base plate and the cylinder form.

In molding the cylinder the form was filled about one-third full and the concrete puddled with a ¾-in. steel bar about 21 in. long. Filling and puddling were continued until the form was full. The top was

*(Note added at Third Printing, September, 1922). Present practice in making the slump test for consistency or workability of concrete requires the use of a 4 by 8 by 12-in. truncated cone. For concrete of a given consistency the cone gives slumps about 1/3 less than the cylinder. The truncated cone is specified in the Progress Report of the Joint Committee on Standard Specifications for Concrete and Reinforced Concrete and is used in the Tentative Specifications for Workability of Concrete for Concrete Pavements of the American Society for Testing Materials.

TABLE 4—WEAR AND COMPRESSION TESTS OF CONCRETE.

Hand-mixed concrete. 1: 4 by volume.
Aggregate graded 0-1¼ in.
The same sand used in all tests.
Coarse aggregate consisted of pebbles or crushed limestone of the same grading.
The specimens were stored for the period shown in damp sand, the remainder of the time in the air of the Laboratory. Age at test, 4 months.
Wear tests made in Talbot-Jones rattler—total of 1800 revolutions.
Wear tests are average of five 8 by 8 by 5-in. blocks.
Compression tests are average of two 6 by 12-in. cylinders.
The second set of tests in each group was made 2 to 4 weeks after the first.

Coarse Aggregate	Mixing Water		Depth of Wear—Inches 8 by 8 by 5-in. Blocks				Compressive Strength lb. per sq. in. (6 by 12-in. Cylinders)			
	Relative Consistency	Water-Ratio	Damp Sand Storage	21 days in Damp Sand	3 days in Damp Sand	Air Storage	Damp Sand Storage	21 days in Damp Sand	3 days in Damp Sand	Air Storage
Pebbles	.90	.66	.53	.34	.82	1.29	4970	5310	2890	2110
			.54	.51	.84	.91	4990	5150	2720	2260
			.54	.43	.83	1.10	4980	5230	2810	2190
Crushed Limestone	.90	.66	.48	.....	.....	.....	5970	.....	.....	.....
			.52	.....	.....	.....	5700	.....	.....	.....
			.50				5890			
Pebbles	1.00	.73	.54	.52	.83	1.01	5530	4550	3040	2290
			.52	.41	.78	1.10	4760	4960	2960	2020
			.53	.47	.81	1.06	5200	4760	3000	2160
Crushed Limestone	1.00	.73	.34	.....	.....	.....	5800	.....	.....	.....
			.46	.....	.....	.....	5280	.....	.....	.....
			.40				5540			
Pebbles	1.10	.81	.52	.51	1.00	1.23	4470	3940	2350	2240
			.56	.54	.98	1.02	5020	4220	2410	2050
			.54	.53	.99	1.12	4750	4080	2380	2150
Crushed Limestone	1.10	.81	.48	.....	.....	.....	5390	.....	.....	.....
			.52	.....	.....	.....	5540	.....	.....	.....
			.50				5470			
Pebbles	1.25	.91	.57	.51	.96	1.56	4700	4350	2360	1640
			.63	.56	1.25	1.64	4490	3640	1900	1710
			.60	.54	1.10	1.60	4600	4000	2130	1680
Crushed Limestone	1.25	.91	.58	.....	.....	.....	4320	.....	.....	.....
			.56	.....	.....	.....	4850	.....	.....	.....
			.57				4590			
Pebbles	1.35	.99	.59	.69	1.49	2.40	3860	2570	1400	1420
			.66	.69	1.61	1.51*	3650	3190	1310	1250
			.63	.69	1.55	1.51	3760	2880	1360	1340
						1.51*				
Crushed Limestone	1.35	.99	.59	.....	.....	.....	3910	.....	.....	.....
			.61	.....	.....	.....	3820	.....	.....	.....
			.60				3870			
Pebbles	1.50	1.09	.74	.85	2.34	1.68	3740	2300	1330	1280
			.73	.92	2.00*	....†	3530	2440	1090	1240
			.73	.89	....†	1.68	3640	2370	1210	1260
					2.00*					
Crushed Limestone	1.50	1.09	.60	.....	.....	.....	2640	.....	.....	.....
			.68	.....	.....	.....	3190	.....	.....	.....
			.64				2920			

* Omitting one badly damaged block.
† One block disintegrated, allowing entire charge to fall out after about 1100 revolutions.

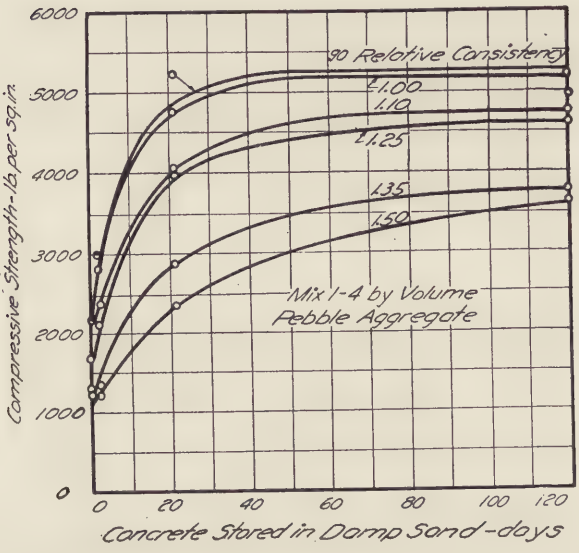


FIG. 5—EFFECT OF CURING CONDITIONS ON THE STRENGTH OF CONCRETE.

Compression tests of 6 by 12-in. cylinders at age of 4 months. Each value is the average of four tests made on two different days. Same data as in Fig. 3.

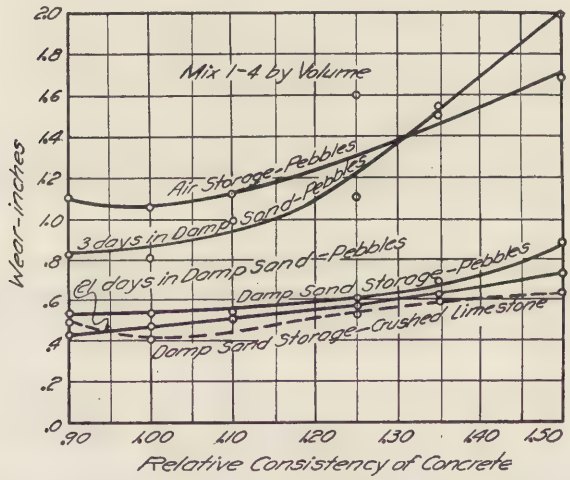


FIG. 6—EFFECT OF QUANTITY OF MIXING WATER ON THE WEAR OF CONCRETE.

Wear tests of 8 by 8 by 5-in. blocks at age of 4 months. Each value is the average of 10 blocks made on two different days. Same data as in Fig. 7.

leveled off with a bricklayer's trowel. About 3 to 4 hours after molding, a thin layer of neat cement paste (which was mixed at the same time or before the concrete) was spread over the top of the cylinder. A piece of plate glass and a sheet of paraffined paper were used to form a cap, which made a smooth, square end for loading. The glass remained in place until the form was removed.

This method of capping is much better than setting the specimens in plaster of paris or a cement-plaster mixture immediately before testing. It has the following advantages:

(1) The cap is just as strong and stiff as the concrete and forms an integral part of the specimen.

(2) The time and labor required is a small part of that necessary with the plaster method.

(3) The plate glass prevents evaporation of water during the period the concrete is in the form.

(4) The cylinder is ready for test at any time without further preparation.

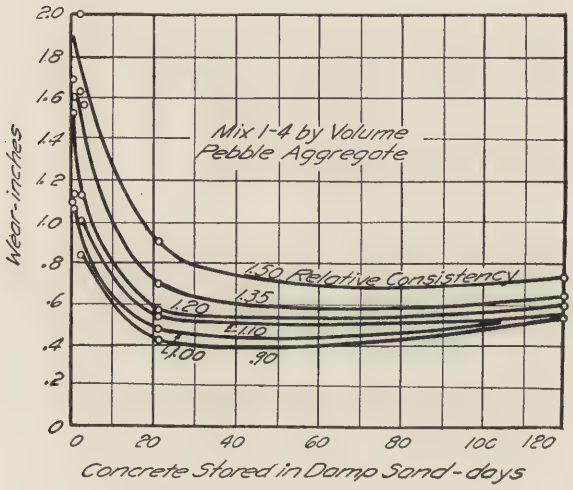


FIG. 7—EFFECT OF CURING CONDITIONS ON THE WEAR OF CONCRETE.

Wear tests of 8 by 8 by 5-in. blocks at age of 4 months. Each value is the average of 10 blocks made on two different days. Same data as in Fig. 6.

The metal forms for the wear blocks were made in gangs of three. The form was set on a sheet of building paper laid directly on the concrete floor. The form was filled before puddling. The top was leveled off with a trowel. After a period of 1 to 2 hours the top of the blocks was finished by hand with a wood float. Instead of capping, the blocks were covered with a sheet of wet building paper and about 3 in. of damp sand. This method prevented loss of water while the blocks were in the forms.

All test pieces were allowed to remain in the metal forms over night. Upon removal of the forms they were stored in the manner indicated in Table 4. Two cylinders and five wear blocks were made in each group before the duplicate sets were begun. The duplicate sets were made two to four weeks after the first.

METHODS OF TESTING.

The compression tests of concrete were made in a 200,000-lb. Olsen universal testing machine. A spherical bearing block was used on top of the cylinders.

Wear tests of concrete were made in the Talbot-Jones rattler. The test pieces consist of blocks 8 in. square and 5 in. in thickness. The blocks are arranged around the perimeter of the drum of the rattler, as shown in Fig. 1. Ten blocks constitute a test set. The ten-side polygon formed by the test blocks presents a nearly continuous surface. The outside diam-

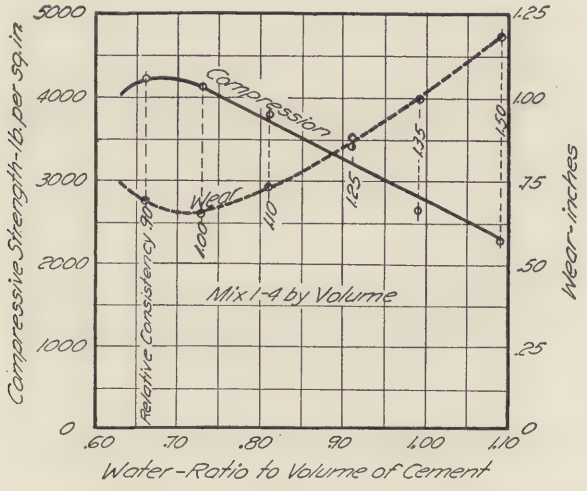


FIG. 8—EFFECT OF QUANTITY OF MIXING WATER ON THE STRENGTH AND WEAR OF CONCRETE.

Average curves from Fig. 3 and 6. The quantity of mixing water is expressed as a ratio to the volume of cement in the batch. Each value for compression is the average of 20 tests (four curing conditions). Each value for wear is the average of 50 tests (four curing conditions). In interpreting this diagram it should be borne in mind that we have averaged the four storage conditions described in Table 4. For best curing conditions the concrete will show a higher strength and much less wear than any indicated on this diagram.

eter of the polygon thus formed is 36 in. and the inside diameter 26 in. During the test the front of the chamber is closed by means of a light steel plate. The abrasive charge consists of 200 pounds of cast-iron balls

(about 133 1⅞ in. and 10 3¾ in. in diameter). These balls conform to the requirements for the standard rattler test of paving brick of the American Society for Testing Materials.

The test consists of exposing the inner faces of the concrete blocks to the wearing action of the charge for 1800 revolutions at the rate of 30 r. p. m. The machine was run for 900 revolutions in one direction, then reversed. Two sets of blocks are tested at once in the machine now in use. Each block was weighed upon removal from the form, upon removal from the damp sand, immediately before and after testing. The loss in weight during the test, reduced to an equivalent depth of wear in inches, was used as a measure of the wear.

Absorption tests were made on two wear blocks from each set of 10. The tests were made when the blocks were about one year old, after having been stored in the open air in the laboratory during the period following the wear test. The blocks were dried to approximately constant weight

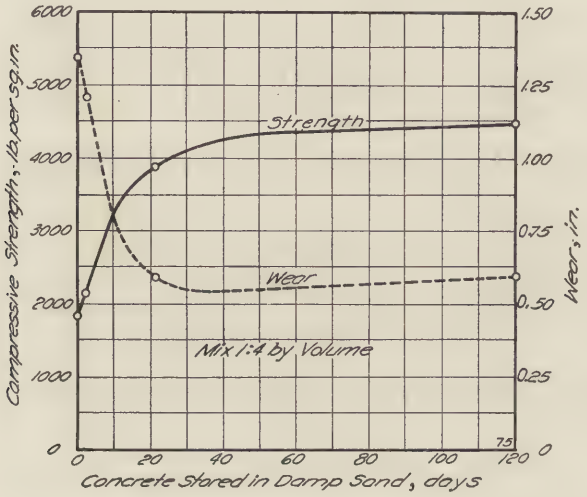


FIG. 9—EFFECT OF CURING CONDITION ON THE STRENGTH AND WEAR OF CONCRETE.

Average curves from Fig. 5 and 7. Each value for compression is the average of 24 tests (four each for six consistencies). Each value for wear is the average of 60 blocks (10 each for six consistencies). The upward trend of the wear curve results from the abnormal wear of the 4-month sand-stored blocks on account of being tested in damp condition.

on a steam radiator, weighed and immersed in water at room temperature. At various intervals they were removed from the water, allowed to drain for about 5 minutes and weighed. The gain in weight was reduced to an equivalent volume of absorbed water.

DISCUSSION OF TESTS.

The tests included in this report consisted of compression tests of 120 6 by 12-in. concrete cylinders and 300 wear tests of 8 by 8 by 5-in. blocks, as well as miscellaneous tests of cement and aggregate. A 1:4 mix was used throughout, with aggregate graded up to 1¼-in. In general the coarse aggregate was pebbles; in one group of tests crushed limestone was used. This mix is approximately the same as that generally used in one-course concrete road construction. Four different curing conditions were used for pebble aggregate as follows:

(1) Damp sand 4 months, tested damp,
(2) Damp sand 21 days, air 99 days,
(3) Damp sand 3 days, air 117 days.
(4) Air of laboratory for entire curing period of 4 months.

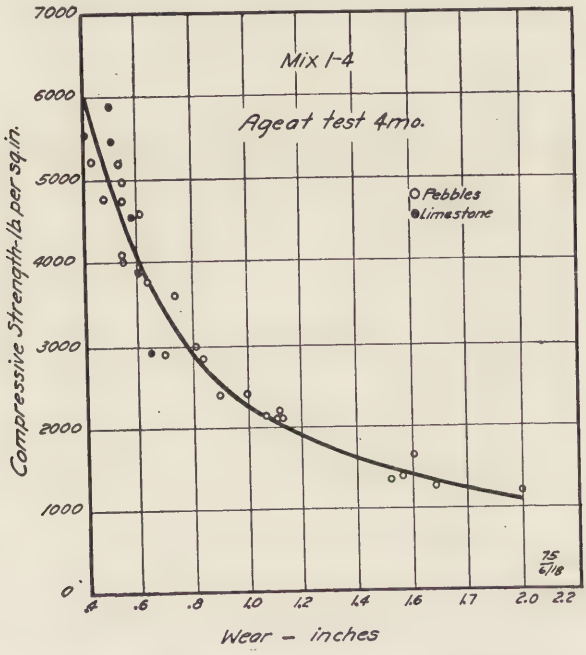


FIG. 10—RELATION BETWEEN THE STRENGTH AND WEAR OF CONCRETE.

Compression tests of 6 by 12-in. cylinders, and wear tests of 8 by 8 by 5-in. blocks at age of 4 months. Each value is based on the averages of four compression tests and 10 wear tests. All consistencies and curing conditions are included.

Group (1) was repeated, using crushed limestone as coarse aggregate. All compression and wear tests were made at age of 4 months. Average values from the strength and wear tests are given in Table 4.

EFFECT OF QUANTITY OF MIXING WATER ON THE STRENGTH OF CONCRETE.

Fig. 3 gives the results of the tests on the effect of quantity of mixing water on the compressive strength of concrete. A separate curve has been drawn for each curing condition. An average curve from these tests will be found in Fig. 8. The remarkable influence of the quantity of mixing water on the strength, other factors being the same, is clearly shown by these curves. It will be remembered that the consistency which we have called 1.00 (normal consistency) is such that a 1:4 mix gives a slump of ½ to 1 in. when the form is slipped off the freshly molded cylinder. A consistency of .90 contains 90 per cent of the amount of water required for normal consistency; a consistency of 1.50 contains

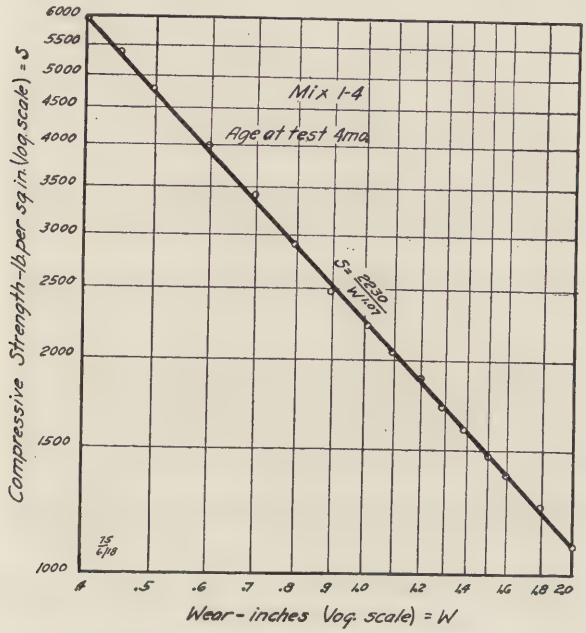


FIG. 11—RELATION BETWEEN STRENGTH AND WEAR OF CONCRETE.
Same data as in Fig. 10, except curve platted on logarithmic scales. The points shown are taken from the curve in Fig. 10.

1½ times the quantity of water used in the normal consistency concrete, etc. The normal consistency concrete may be characterized as plastic; the .90 is somewhat dry; the 1.50 quite wet, but contains much less water than the "sloppy" mixes frequently seen in reinforced concrete work.

It will be noted that there is a rapid falling-off in strength as the water content is increased from normal consistency. With a consistency of 1.25 the strength is reduced to about 75 per cent of the highest; with a consistency of 1.50 the strength is only one-half that which may be

obtained with the same cement content. For wetter mixes the strength would be still further reduced.

In general it is not feasible to use concrete of a consistency which will give maximum strength, since it is somewhat too stiff for satisfactory workability. In concrete road work where hand finishing is used the concrete must be mixed to a consistency varying from 1.10 to 1.15. In other words, we must sacrifice a portion of the possible strength of the concrete in order to secure a workable mix. This consistency will give a slump of 5 to 7 in. If machine finishing is employed, the concrete

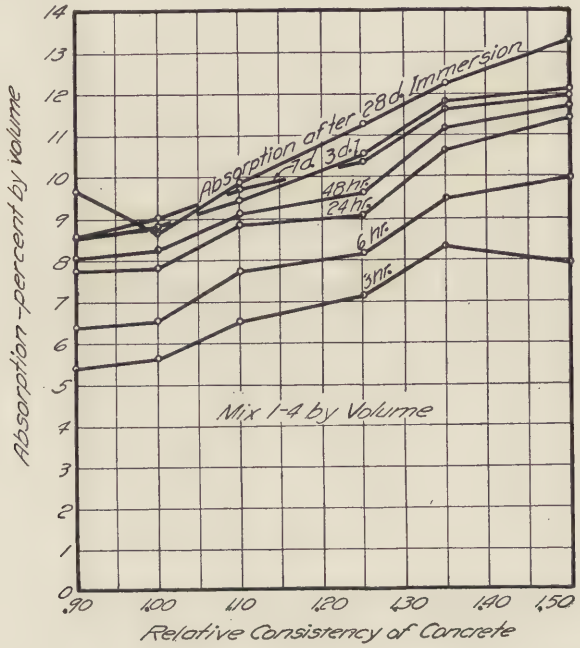


FIG. 12—EFFECT OF QUANTITY OF MIXING WATER ON THE ABSORPTION OF CONCRETE.

Absorption tests of 8 by 8 by 5-in. blocks. Pebble aggregate. Age 1 year. Absorption determined after immersion in water at room temperature. Each value is the average of eight blocks from four different curing conditions—one block from each set of pebble aggregates in Table 5. Absorption is given by volumes; absorption by weight is about 40 per cent of these values.

can be mixed to a consistency corresponding closely to maximum strength. In reinforced concrete work there is in general little excuse for using mixes wetter than 1.25 consistency, corresponding to a slump of 8 to 9 in.

The average curves in Fig. 8 have been platted in terms of the water-ratio instead of the relative consistencies, although relative consistencies are also shown. The water-ratio is the ratio by volume of water to cement in the batch.

FURTHER DISCUSSION OF EFFECT OF QUANTITY OF MIXING WATER ON THE STRENGTH OF CONCRETE.

Many series of tests made in this Laboratory have fully established the fundamental influence of the quantity of mixing water on the strength of concrete.

Fig. 4 gives the average values from a series of tests of this kind in which the compressive strength is platted against the water-ratio of the concrete. In this series the mixes ranged from 1 : 15 up to neat cement. The consistencies were varied over a wide range. The size of the aggre-

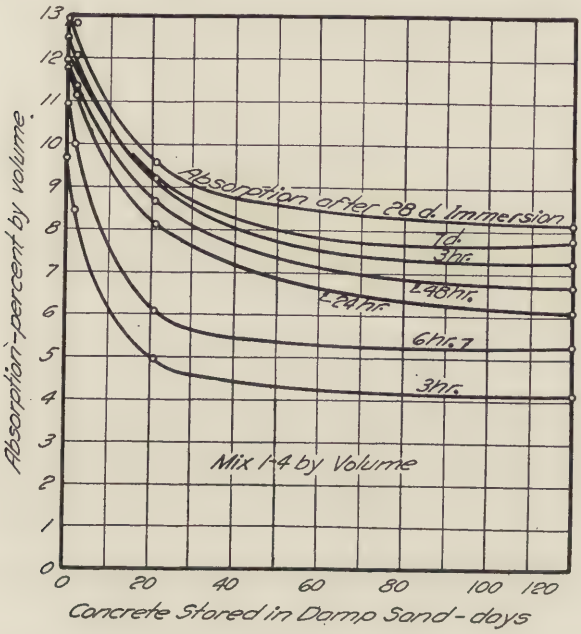


FIG. 13—EFFECT OF CURING CONDITIONS ON THE ABSORPTION OF CONCRETE.

Absorption tests of 8 by 8 by 5-in. blocks. Absorption determined after immersion in water at room temperature. Each value is the average of 12 blocks from six different consistencies. Same data as in Fig. 12. Absorption is given by volumes; absorption by weight is about 40 per cent of these values.

gate ranged from a very fine sand to a coarse concrete aggregate, for all combinations of mix and consistency. Further details of these tests are not given in this report.

In the figure distinguishing marks were used for each mix, but no distinction was made between aggregates of different sizes or concretes of different consistencies. When the compressive strength is platted against the water content in this way a smooth curve is obtained due to

the overlapping of the points for different mixes, consistencies, etc. Values from the dry concretes have been omitted from the diagram; if these were used we should obtain a series of curves dropping downward to the left from the curve shown. It is seen at once that the size and grading of the aggregate and the quantity of cement are no longer of any importance, except in so far as these factors influence the quantity of mixing water required to produce a workable concrete. This gives an entirely new conception of the function of the constituent materials entering into a concrete mixture.

The equation of the curve in Fig. 4 is of the form

$$S = \frac{A}{B^x}$$

where S is the compressive strength of the concrete and x (an exponent) is the ratio of the volume of water to volume of cement in the batch (water-ratio). A and B are constants whose values depend on the quality of the cement used and on other conditions of the test.

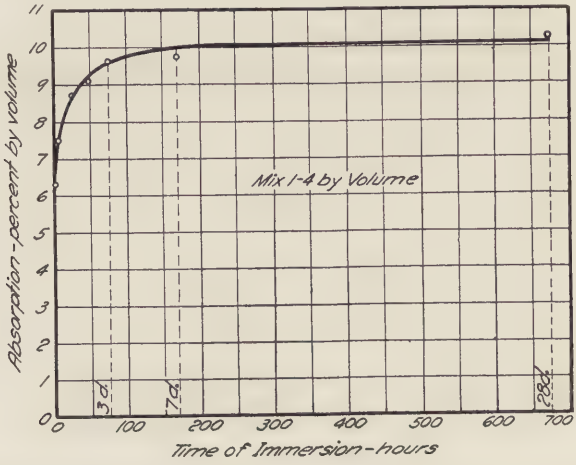


FIG. 14—EFFECT OF TIME OF IMMERSION ON THE ABSORPTION OF CONCRETE.

Absorption tests of 8 by 8 by 5-in. blocks. Absorption determined after immersion in water at room temperature. Each value is the average of 48 tests from six consistencies and four curing conditions. Data from Table 5. Absorption is given by volumes; absorption by weight is about 40 per cent of the these values.

The values of the constants in these tests are shown on the diagram. This equation expresses the law of the strength of concrete so far as variations in the proportions of materials are concerned. It is seen that for given concrete materials the strength depends on only one factor—the water-ratio. Equations which have been proposed for this purpose in the past contain terms which take into account such factors as quan-

TABLE 5—ABSORPTION TESTS OF CONCRETE.

Mix 1:4 by volume. Hand-mixed concrete.

Aggregate graded 0-1¼ in.

The same sand used in all tests—torpedo sand from Elgin, Ill.

Coarse aggregate consisted of pebbles or crushed limestone of same grading.

Age at test 1 year. The tests were made on 8 by 8 by 5-in. concrete blocks which had previously been used in wear tests at the age of 4 months. Immediately after molding the blocks were stored for the period shown in damp sand, the remainder of the time in the air of the Laboratory.

During the absorption test the blocks were immersed in water at room temperature.

Each value is the average of 2 blocks made on different days.

Coarse Aggregate	Mixing Water		Absorption—Per Cent by Volume											
	Relative Consistency	Water-Ratio	Damp Sand Storage	21 days in Damp Sand	3 days in Damp Sand	Air Storage	Damp Sand Storage	21 days in Damp Sand	3 days in Damp Sand	Air Storage	Damp Sand Storage	21 days in Damp Sand	3 days in Damp Sand	Air Storage
			3 Hours				6 Hours				24 Hours			
Pebbles	.90	.66	3.17	3.93	6.41	8.09	3.81	4.49	7.70	9.53	4.99	6.26	8.84	11.00
Cr. Limestone.	.90	.66	4.66	.....	.....	.....	5.15	.....	.....	.....	6.52	.....	.....	.....
Pebbles	1.00	.73	4.47	4.00	6.71	7.32	5.05	4.50	7.96	8.74	6.11	6.05	9.59	9.61
Cr. Limestone.	1.00	.73	2.53	.....	.....	.....	3.47	.....	.....	.....	4.71	.....	.....	.....
Pebbles	1.10	.81	2.58	5.07	8.18	10.30	4.77	6.06	9.58	10.66	5.11	8.00	10.60	11.80
Cr. Limestone.	1.10	.81	2.89	.....	.....	.....	4.16	.....	.....	.....	4.75	.....	.....	.....
Pebbles	1.25	.91	5.56	4.23	8.52	10.20	5.48	5.82	9.91	11.40	5.99	7.67	10.60	12.10
Cr. Limestone.	1.25	.91	4.30	.....	.....	.....	5.27	.....	.....	.....	6.02	.....	.....	.....
Pebbles	1.35	.99	4.58	6.25	11.90	10.70	5.97	7.63	12.81	11.61	7.21	9.86	13.60	11.90
Cr. Limestone.	1.35	.99	4.72	.....	.....	.....	6.23	.....	.....	.....	7.40	.....	.....	.....
Pebbles	1.50	1.09	4.58	6.36	9.11	11.60	6.56	7.85	11.92	13.65	7.18	10.90	13.50	14.30
Cr. Limestone.	1.50	1.09	5.07	.....	.....	.....	5.52	.....	.....	.....	8.44	.....	.....	.....
			48 Hours				3 Days				7 Days			
Pebbles	.90	.66	5.08	6.76	9.06	11.36	6.08	7.06	9.35	11.75	6.46	7.31	9.44	11.16
Cr. Limestone.	.90	.66	6.74	.....	.....	.....	6.03	.....	.....	.....	6.98	.....	.....	.....
Pebbles	1.00	.73	6.20	7.06	10.00	9.89	6.54	7.72	10.58	10.53	7.24	7.55	10.34	10.90
Cr. Limestone.	1.00	.73	4.85	.....	.....	.....	5.56	.....	.....	.....	5.76	.....	.....	.....
Pebbles	1.10	.81	5.49	9.26	9.98	11.85	6.88	8.70	10.74	12.35	6.76	9.72	11.45	10.95
Cr. Limestone.	1.10	.81	5.26	.....	.....	.....	6.20	.....	.....	.....	6.90	.....	.....	.....
Pebbles	1.25	.91	7.30	7.94	11.20	12.00	7.65	9.22	13.05	12.30	7.42	9.14	13.50	11.50
Cr. Limestone.	1.25	.91	6.54	.....	.....	.....	7.08	.....	.....	.....	8.06	.....	.....	.....
Pebbles	1.35	.99	8.05	10.14	14.20	12.30	8.94	10.42	14.75	13.22	8.98	10.21	14.40	12.97
Cr. Limestone.	1.35	.99	7.91	.....	.....	.....	8.35	.....	.....	.....	8.85	.....	.....	.....
Pebbles	1.50	1.09	8.02	10.95	13.50	14.45	8.49	11.45	13.65	14.86	9.92	10.81	12.92	14.32
Cr. Limestone.	1.50	1.09	8.82	.....	.....	.....	9.16	.....	.....	.....	9.10	.....	.....	.....
			28 Days											
Pebbles	.90	.66	9.07	7.82	9.63	12.22								
Cr. Limestone.	.90	.66	7.54	.....	.....	.....								
Pebbles	1.00	.73	5.68	7.84	10.92	10.25								
Cr. Limestone.	1.00	.73	5.92	.....	.....	.....								
Pebbles	1.10	.81	7.00	9.43	11.68	11.27								
Cr. Limestone.	1.10	.81	5.64	.....	.....	.....								
Pebbles	1.25	.91	7.88	9.84	14.25	13.18								
Cr. Limestone.	1.25	.91	8.30	.....	.....	.....								
Pebbles	1.35	.99	9.13	10.74	15.08	14.19								
Cr. Limestone.	1.35	.99	9.43	.....	.....	.....								
Pebbles	1.50	1.09	10.15	11.72	15.40	16.50								
Cr. Limestone.	1.50	1.09	9.23	.....	.....	.....								

tity of cement, proportions of fine and coarse aggregate, voids in aggregate, etc., but they have uniformly omitted the item which is of most importance; that is, the water. The relation given above holds so long as the concrete is not too dry for maximum strength, and the aggregate not too coarse for a given quantity of cement; in other words, so long as we have a workable concrete.

The strength of the concrete responds to changes in water, regardless of the reason for these changes. The water-ratio may be changed due to any of the following causes:

(1) Change in mix (cement content).
(2) Change in size or grading of aggregate.
(3) Change in relative consistency.
(4) Any combination of (1) to (3).

TABLE 6—UNIT WEIGHT OF CONCRETE.

Mix 1:4 by volume. Hand-mixed concrete.
Weighed immediately before test at age of 4 months.
Aggregate graded 0-1¼ in.
The same sand used in all tests.
Coarse aggregate consisted of pebbles or crushed limestone of same grading.
The tests were made on 8 by 8 by 5-in. blocks and 6 by 12-in. cylinders.
Test pieces were stored for the period shown in damp sand, the remainder of the time in the air of the Laboratory.
Each value is the average of 4 cylinders and 10 wear blocks.

Coarse Aggregate	Mixing Water		Weight—lb. per cu. ft.			
	Relative Consistency	Water Ratio	Damp Sand Storage	21 da. in Damp Sand	3 da. in Damp Sand	Air Storage
Pebbles	.90	.66	155.8	148.5	147.0	147.0
Crushed Limestone	.90	.66	152.5	.....	.....	.....
Pebbles	1.00	.73	157.0	153.0	152.0	151.0
Crushed Limestone	1.00	.73	152.0	.....	.....	.....
Pebbles	1.10	.81	156.9	152.0	150.5	149.8
Crushed Limestone	1.10	.81	156.0	.....	.....	.....
Pebbles	1.25	.91	155.9	152.0	148.5	148.0
Crushed Limestone	1.25	.91	156.2	.....	.....	.....
Pebbles	1.35	.99	156.9	152.0	149.8	150.2
Crushed Limestone	1.35	.99	155.6	.....	.....	.....
Pebbles	1.59	1.09	154.8	149.5	148.2	148.0
Crushed Limestone	1.50	1.09	156.0	.....	.....	.....

In certain instances a 1:9 mix is as strong as a 1:2 mix, depending only on water content. It should not be concluded that these tests indicate that lean mixes can be substituted for richer ones without limit. We are always limited by the necessity of using sufficient water to secure a workable mix. So in the case of the grading of aggregates. The workability of the mix will in all cases dictate the minimum quantity of water that can be used. The importance of the workability factor in concrete is therefore brought out in its true relation.

Designing concrete mixes resolves itself into the problem of producing a workable concrete with a given water-ratio using a minimum of cement; or the converse, of producing a workable concrete which has the lowest water-ratio for a given quantity of cement. The methods of securing the best grading of aggregate and the use of the driest practicable concrete are seen to be only devices for accomplishing the above-mentioned results. A forthcoming Bulletin on the "Design of Concrete Mixtures"* will give further details of the principles underlying the proportioning of concrete, and discuss their application to practical problems.

The influence of the water-ratio of concrete on its strength will be shown by the following considerations: One pint more water than necessary to produce a plastic concrete in a 1:4 mix reduces the strength to the same extent as if we should omit 2 to 3 pounds of cement from a one-bag batch.

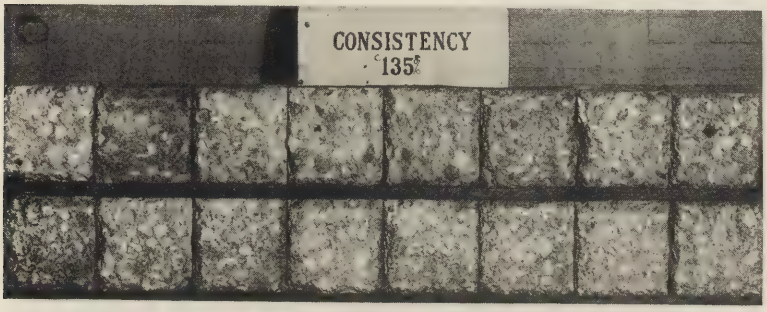


FIG. 15—FRONT VIEW OF WEAR BLOCKS AFTER TEST.

Top row, gravel as coarse aggregate.
Bottom row, crushed limestone as coarse aggregate.

Our studies give us an entirely new conception of the function performed by the various constituent materials. The use of a coarse, well-graded aggregate results in no gain in strength unless we take advantage of the fact that the amount of water necessary to produce a plastic mix can thus be reduced. In a similar way we may say that the use of more cement in a batch does not produce any beneficial effect, except from the fact that a plastic, workable mix can be produced with relatively less water.

The reason a rich mixture gives a higher strength than a lean one is not that more cement is used, but because the concrete can be mixed (and usually is mixed) with a lower water-ratio in the case of the richer mixtures than for the lean ones. If advantage is not taken of the fact

* See Bulletin 1, Structural Materials Research Laboratory.

that in a rich mix relatively less water can be used, no benefit will be gained as compared with a leaner mix. In all this discussion the quantity of water is compared with the quantity of cement in the batch (cubic feet of water to one sack of cement) and not to the weight of dry materials or of the concrete, as is generally done.

For the other curves showing the strength water-ratio relation, see paper on "Time of Mixing Concrete," referred to on page 1.

EFFECT OF QUANTITY OF MIXING WATER ON THE WEAR OF CONCRETE.

Fig. 6 and 8 give the results of tests to determine the effect of quantity of mixing water on the wear of concrete. It will be noted that the depth of wear is expressed in inches. The wear-water-ratio relation



FIG. 16—SIDE VIEW OF CONCRETE BLOCKS AFTER WEAR TEST.

is just opposite to that found in the strength tests; in other words, a high strength is accompanied by low wear, and vice versa. If the wear curve in Fig. 8 were inverted we should have almost a duplicate of the strength curve. In general, the lowest wear is found at about the same water-ratio as the highest strength. The average curves (Fig. 8) show that maximum strength and minimum wear come at a consistency of about .95, or a water-ratio of about .70. It should be pointed out that for other mixes the best results would probably be found at about the same relative consistency, but at a different water-ratio. For a given consistency the water-ratio is higher for lean mixes and lower for rich mixes.

The relation between the depth of wear and the water-ratio of the concrete for blocks stored for 21 days in damp sand is expressed by the equation

$$W = 0.15\ (4.8^{x}).$$

Where W is the depth of wear expressed in inches, and x (an exponent) is the water-ratio. A similar relation was found in the series of wear tests in the paper on "Time of Mixing Concrete," referred to above.

WATER REQUIRED FOR CONCRETE.

Since the quantity of mixing water exerts such an important influence on the strength and other properties of concrete, it will be of interest to examine the factors which influence the amount of water required for satisfactory results. The function of water in concrete is twofold:

(1) To supply the water necessary for hydration of the cement,

(2) To produce a plastic mixture.

While the exact quantity of water required under (1) has not been determined except in certain instances, it is generally agreed that the quantity used in concrete is greatly in excess of that necessary for hydration of the cement. The bulk of the water in concrete is used in order to produce a plastic or workable mix. The exact quantity required for this purpose depends on the materials used, nature of the work, and methods of handling and finishing.

It is, in general, impracticable to state definitely the quantity of water which should be used, since this depends on many factors, such as:

(1) Relative consistency which must be used, which is dictated by the nature of the work,
(2) Normal consistency of the cement,
(3) Quantity of cement,
(4) Size and grading of the aggregate,
(5) Absorption of the aggregate,
(6) Moisture content of the aggregate,
(7) Admixtures which may be used.

A water formula has been developed which takes into account all these elements; for further details see Bulletin 1, "Design of Concrete Mixtures."

The quantity of water which affects the water-ratio as given in Fig. 8 is only such a part of the whole as affects the cement. In other words, the water which is absorbed by the aggregate is not considered as influencing the water-ratio. This makes it plain that the absorption of the aggregate must be taken into account if concretes from widely different aggregates are being compared. Many serious errors have been made in drawing conclusions from tests, due to failure to take into account the influence of absorption, grading of aggregates, etc., on the water content of the concrete.

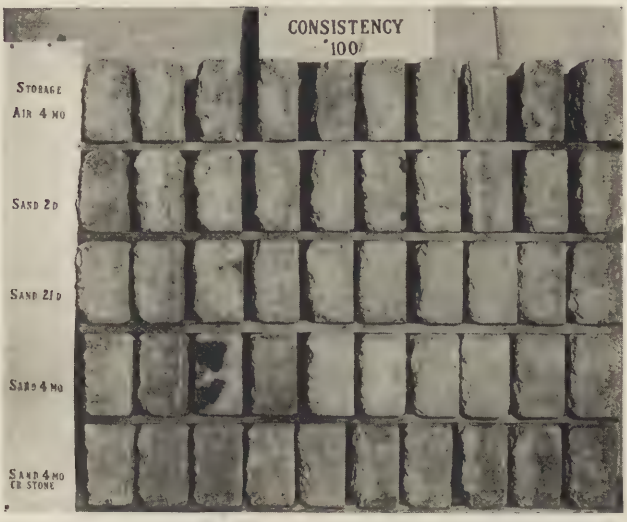


FIG. 17—SIDE VIEW OF WEAR BLOCKS AFTER TEST.
The effect of curing condition on wear is clearly shown.



FIG. 18—SIDE VIEW OF WEAR BLOCKS AFTER TEST.
The effect of curing condition on wear is clearly shown.

In general, it is impracticable to determine in advance the exact quantity of water required for concrete mixes, largely due to two causes: (1) Inability to determine in advance the lowest relative consistency which may be used and still produce a workable concrete; (2) varying moisture content of aggregates.

Table 7 may be of interest in indicating the approximate quantities of water necessary for certain mixtures. It is assumed that a well-graded aggregate up to 1½ in. in size will be used. Only under the most favorable conditions can the minimum values be used; in general, the minimum values need not be exceeded.

TABLE 7.—QUANTITY OF WATER REQUIRED FOR MIXING CONCRETE.

Mix		Approximate Mix as Usually Expressed			Water Required (Gallons per Sack of Cement)	
Cement	Volume of Aggregate After Mixing	Cement	Aggregate		Minimum	Maximum
			Fine	Coarse		
1	7¾	1	3	6	8¼	8¾
1	6½	1	2½	5	7¼	7¾
1	5	1	2	4	6	6½
1	4½	1	2	3	5¾	6¼
1	4	1	1½	3	5½	6
1	3	1	1¼	2½	5	5½

Without regard to the actual *quantity* of mixing water, the following rule is a safe one to follow:

> "Use the *smallest quantity* of mixing water that will produce a workable mix."

The importance of methods of proportioning, mixing, handling, placing or finishing concrete which will enable the builder to reduce the water content to a minimum is at once apparent.

EFFECT OF CURING CONDITION ON THE STRENGTH OF CONCRETE.

The effect of curing condition on the compressive strength of concrete is shown in Fig. 5; an average curve is given in Fig. 9. All consistencies of concrete show great increases in strength under favorable curing conditions as compared with specimens which were allowed to dry out at once. The drier mixes show a more rapid improvement due to storage in a damp place during the first few days than the wetter ones. Even 3 days in damp sand shows an increase in strength of the drier concretes of about 35 per cent as compared with the specimens stored in open air for the entire period. It should be borne in mind that in the most unfavorable case used in the experiments the concrete was in the steel form for 1 day with only the top exposed, consequently the conditions were more favorable than those frequently found in summer weather or in arid regions where the concrete is exposed to rapid evaporation of the mixing water from the moment it is placed.

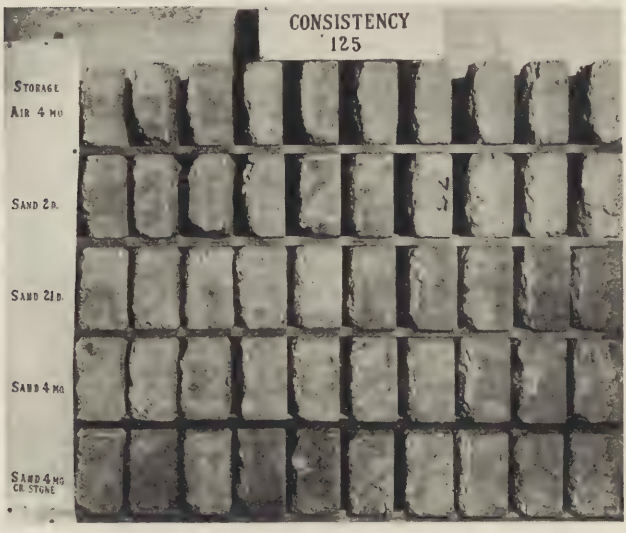


FIG. 19—SIDE VIEW OF WEAR BLOCKS AFTER TEST.
The effect of curing condition on wear is clearly shown.

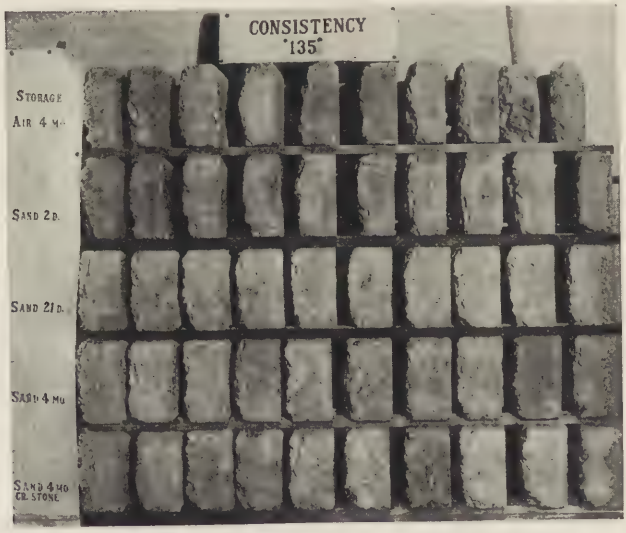


FIG. 20—SIDE VIEW OF WEAR BLOCKS AFTER TEST.
The effect of curing condition on wear is clearly shown.

The concrete stored for 4 months in damp sand and tested damp is 2½ to 3 times as strong as similar concrete which has been exposed to room atmosphere for the same period. Protecting the concrete from drying out for only 10 days (taking values from Fig. 5 and 9) gives an increase in strength of about 75 per cent for the drier consistencies.

EFFECT OF CURING CONDITION ON THE WEAR OF CONCRETE.

The effect of curing condition on the wear of concrete is no less striking than the effect on the strength.

It will be seen in Fig. 7 that the blocks stored for the entire period of 4 months in damp sand showed more wear in most instances than those which had been stored for 21 days in damp sand and the remainder of the time in air. This peculiar result is no doubt due to the fact that the concrete was tested in a damp condition, and does not indicate that the longer period in damp sand is injurious. The comparison would have been more nearly correct if the blocks had been allowed to dry out a few days before testing. These results do show that concrete in a wet or damp condition suffers more from wear than when dry. It is a matter of common experience that non-metallic materials, such as timber, terra cotta, concrete, stone, etc., which absorb water, show a lower strength in a wet condition than when dry. Additional tests will be required to show the exact effect of moisture content on strength and wear of concrete, other factors being the same.

It is not necessary to speculate on the probable effect of moisture in the concrete in order to secure valuable information from these tests. The drier mixes show an increase in wear from .50 in. for concrete stored in damp sand for 21 days to 1.10 in. for concrete in air for entire period; the tests show that 10 days in damp storage gives a wear of about .65 in. For the wetter mixes the wear after 21 days in damp sand is about .85 in.; for 10 days, 1.15 in.; for air storage throughout, probably 2 in. In the wetter consistencies the tests were not carried to completion on account of the failure of certain blocks, which caused the entire ring to collapse.

The photographs in Fig. 16 to 21 show side views of the blocks after test. The effects of both consistency and curing condition are clearly shown by the relative thickness of the blocks.

RECAPITULATION OF EFFECT OF CONSISTENCY AND CURING CONDITION.

In view of the important influence of consistency and curing conditions of concrete shown by these tests, it seems doubtful if there is any phase of concrete work which will pay such high dividends as a little care to see that proper consistency is used and that desirable curing conditions are provided. In many instances the quality of the concrete could be vastly improved at trifling expense; but nothing is done because those in charge do not appreciate the importance of care in these directions. The writer is convinced that practically all of the faults from concrete floors follow from these two causes. Excessive wear and dusting are certain

to result in a floor in which the concrete is never allowed to have the water necessary for hydration of the cement. It is notable that dusting never occurs on a concrete road, for the reason that it gradually gets the water necessary for hydration from rain or snow. However, due to low wearing resistance at early periods, resulting from premature drying, it may be badly worn before rain comes.

An excess of mixing water is a serious fault in concrete. If, in addition, the concrete is allowed to dry out at once it is almost certain to be a failure, if subjected to wear, and will give very low strength. For the two wettest consistencies and the two most unfavorable curing conditions,

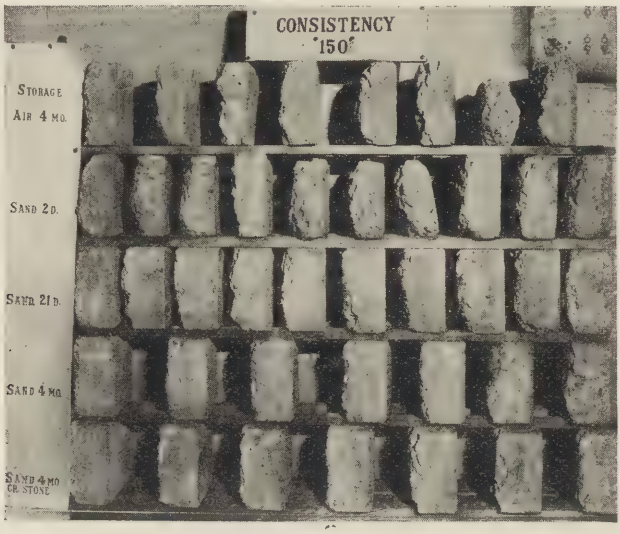


FIG. 21—SIDE VIEW OF WEAR BLOCKS AFTER TEST.

Some of the blocks which were stored for the entire 4 months in air were completely broken up before the end of the test run. The blocks missing from the two lower rows were lost before the photograph was taken.

the compressive strength of the pebble concrete was 1300 lb. per sq. in.; for the two most favorable curing conditions and the three driest consistencies the average compressive strength was 4850 lb. per sq. in.—an increase of 275 per cent. In the case of the wear tests the corresponding values are 1.70 in. and .50 in.; an increase of 240 per cent. The comparison in the wear test is not as unfavorable as it should have been, since the poorer blocks broke up before the test was completed.

Proper curing of concrete is second only in importance to the control of mixing water. The rule stated above with reference to water content may now be extended to the following:

> Use the *smallest quantity* of mixing water that will produce a workable concrete, then allow the concrete to have *as much water as possible* during the period of curing.

All concrete should be protected against premature drying for at least one week, and longer if practicable. This period should be extended to 10 days or two weeks in cool weather, or where the concrete is to be subjected to heavy traffic at an early age.

Covering with damp sand or earth, or wet burlap are excellent methods of curing. The practice of "ponding" is common in road construction. The writer wishes to offer a word of caution with reference to the use of wet sawdust for covering concrete floors. Sawdust may have most harmful results, on account of the organic acids present.

Compression tests of concrete made in other series show that the strength of concrete increases indefinitely, so long as it is not permitted to dry out.*

RELATION BETWEEN STRENGTH AND WEAR OF CONCRETE.

The relation between strength and wear of concrete in this series is shown in Fig. 10. All tests have been platted. Each value is based on the average of four compression tests and 10 wear tests. This diagram shows that a definite relation exists between strength and wear at least for the conditions of these tests; that is, for concrete of different consistencies and curing conditions. Further tests will be necessary to show whether or not this relation is entirely general for other aggregates, etc.

Fig. 11 is the same curve platted to a logarithmic scale. The straight line in this diagram enables us to devise the equation:

$$S = \frac{2230}{W^{1.07}}$$

as showing the relation between the variables; where S = compressive strength in pounds per square inch and W = the depth of wear in inches.

A similar relation from another series of strength and wear tests made in this laboratory will be found in Fig. 14 and 15 of the paper on "Effect of Time of Mixing," referred to on page 1.

In the earlier series of tests the relation between strength and wear of concrete was expressed by

$$S = \frac{1800}{W^{1.30}}$$

The agreement between the equations from the two different series of tests is quite close when we consider that the earlier series was tested at 2 mo. and the later at 4 mo.

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* See "Effect of Age on the Strength of Concrete," by D. A. Abrams, Proc. Am. Soc. Testing Mat., Part II, 1918; also *Concrete*, July, 1921, p. 14.

COMPARISON OF PEBBLE AND CRUSHED STONE AGGREGATE.

Crushed limestone was used as coarse aggregate in one group of tests. In general the limestone concrete gave somewhat higher strength and lower wear than the gravel concrete using the same sand and the same water and cement. However, the tests do not cover a sufficient range to justify definite comparisons of the merits of the two types of aggregate. Both of the aggregates used in this series were of high grade and gave good results in the tests. Other tests now under way and planned for the future are expected to give definite information on the relative merits of different aggregates.

METHOD OF MAKING WEAR TESTS.

The Talbot-Jones rattler has been found entirely successful as a method of studying the wear of concrete in the laboratory. The results of the tests thus far completed and the definite relations found between the wear and strength have given considerable confidence to this method of testing. The abrasive charge of 200 pounds of cast-iron balls, and the rate and number of revolutions used, gives a wearing action suited for a wide range in the properties of concrete. A very poor concrete may be entirely destroyed, a high-grade concrete will show a wear of ½ inch or less.

The test gives a combination of abrasion and impact that cannot be withstood by an inferior concrete. The severity of the impact may be seen from the fact that frequently the 1⅞-in. cast-iron balls are broken during the test. While the test does not fully duplicate the action of traffic, it furnishes a valuable guide to the relative effects of different methods of treatment, materials, etc., for use in pavement construction.

This method of making wear tests of concrete is believed to have the following advantages as compared with other methods which have been used or proposed for this purpose:

(1) The concrete is subjected to a treatment which approximates that of service.

(2) The test piece is of usual form and of sufficient size that representative concrete can be obtained.

(3) The test pieces are convenient to make, store and handle, and require a relatively small quantity of concrete.

(4) The cost of tests is not excessive.

(5) The machine used is found in a number of testing laboratories.

(6) The wearing action takes place on the top or finished surface of the concrete. This makes it possible to study the effect of various surface treatments and finishes.

(7) Several tests may be made at the same time, thus enabling more representative results to be obtained.

(8) Tests may be made on sections of concrete cut from roads which have been in service.

(9) Other paving materials, such as brick, granite blocks, etc., may be tested in the same manner as the concrete.

ABSORPTION TESTS OF CONCRETE.

Absorption was determined on two wear blocks from each set of 10, after immersion in water for periods of 3 hours to 28 days. It should be noted that absorption tests were made on blocks at the age of 1 year, which had been tested for wear at 4 months.

The results of absorption tests are given in Table 5, and in Fig. 13 and 14. In Fig. 13 all consistencies for a given curing condition have been averaged. It is interesting to note that the absorption is influenced by the curing condition of the concrete in the same way as the wear. (Compare Fig. 13 and 7.) The curing condition that gives high wear, gives high absorption, and vice-versa.

The effect of consistency and curing condition on absorption is shown by an average absorption of 5.77 per cent for the most favorable conditions after 24-hour immersion and 12.6 per cent for the most unfavorable conditions. The absorption is here given by volumes; the absorption by weight would be only about 40 per cent of these values.

The effect of time of immersion on the absorption is shown in Fig. 14; all consistencies and curing conditions have been averaged for a given time of immersion.

UNIT WEIGHT OF CONCRETE.

The unit weight of all test pieces was determined immediately before test at the age of 4 months. The values are given in Table 6. Each value is the average from four cylinders and 10 wear blocks. The weight of the concrete is little affected by the consistency, but is greatly influenced by the curing condition. The weights of the specimens stored for 4 months in damp sand cannot be compared directly with the others, since they contained free moisture; that is, water in the uncombined state. A comparison of the average weights of all consistencies for the other curing conditions shows that the concrete stored 3 days in damp sand took up .33 lb. more water and that stored for 21 days in damp sand 2.16 lb. more water per cubic foot than that stored in air throughout the 4 months. Since all test pieces were in the same room-dry condition when the weights were determined, it seems that these values may be taken as approximate measures of the additional quantities of water which have entered into chemical combination with the cement, due to storage in a damp place for these periods.

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Bulletin 3

Structural Materials Research Laboratory
Lewis Institute
Chicago

Effect of Vibration, Jigging and Pressure on Fresh Concrete

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FOREWORD

This report was originally published in the Proceedings of the American Concrete Institute, Vol. XV, 1919; it was reprinted as Bulletin 3 of this Laboratory, November, 1919.

In this second printing, a few footnotes have been added which show deviations of present practice from that followed in these tests.

There has been a marked increase in the use of vibrating and jigging equipment during the past three years, especially in products plants.

For the assistance of those who may wish to look up earlier work on the subject, a brief list of references has been added.

EFFECT OF VIBRATION, JIGGING AND PRESSURE ON FRESH CONCRETE.

By Duff A. Abrams.

Introduction.

An experimental study of the effect of vibration and pressure on fresh concrete on its strength and other properties is of interest in view of the frequent use of such devices as hand-hammering of forms, or air-hammering, jigging or vibration as an aid in placing concrete. Such methods are particularly applicable to the construction of reinforced-concrete ships and houses, where thin sections and a multiplicity of reinforcing members are of common occurrence. Jigging or vibrating machines are frequently used in concrete products plants. The effect of pressure on fresh concrete is of interest in certain problems of concrete design.

Little attention has heretofore been given to the experimental study of the effects produced by vibration and jigging fresh concrete. A few tests were made in a study of the effect of pressure on fresh cement paste in a confined space by James E. Howard, at Watertown Arsenal.[1] The effect of pressure on the compressive strength and bond was studied by the writer at the University of Illinois in 1913.[2] Since the tests reported herein were completed, Prof. F. P. McKibben has published a report on compression tests of concrete columns which set under pressure.[3]

The tests included in this report were made as a part of the experimental studies of concrete and concrete materials being carried out through the cooperation of Lewis Institute and the Portland Cement Association.

Outline of Tests.

The tests included in this report cover the following topics:

1. Different methods of hand-molding of test cylinders.
   - (*a*) Puddling with $\frac{5}{8}$-in. round steel bar (varying number of strokes).
   - (*b*) Tamping (tampers of different size).
   - (*c*) Tapping metal forms after puddling.
2. Effect of vibrating fresh concrete (small electric motor, Fig. 1.)
   - (*a*) Time of vibration varied up to 1 min.
3. Effect of jigging fresh concrete (using machine shown in Fig. 2).
   - (*a*) Concrete of different mixes (1:7 to 1:3).
   - (b) Concrete of different relative consistencies (0.70 to 1.25).

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[1]Cement Age, June, 1905.

[2]"Tests of Bond between Concrete and Steel." Bulletin 71, Ill. Engineering Experiment Station, 1914.

[3]Eng. News-Rec., Dec. 5, 1918.

(*c*) Using aggregate of different grading (fineness modulus 4.00 to 6.50).
(*d*) Using aggregate of different sizes (0-28 sand to 0-1½-in. concrete aggregate).
(*e*) Using coarse aggregate of different shape (pebbles and crushed stone).
(*f*) Effect of rate of jigging (0 to 150 r. p. m.).
(*g*) Effect of height of drop (0 to 0.50 in.).
(*h*) Effect of length of time jigged (up to 3 min.)
(*i*) Effect of age of concrete before jigging (up to 6 hr.).
(*j*) Jigged with 30-lb. weight on top of fresh concrete.
(*k*) Hand puddling on jigging machine while in operation.

4. Effect of pressure on fresh concrete (method of applying the higher pressures shown in Fig. 3).
(*a*) Using different pressures (0 to 500 lb. per sq. in.).
(*b*) Effect of duration of pressure (15 min. to 16 hr.).
(*c*) Effect of removal of water by pressure.

This series included 900 compression tests of 6 by 12-in. concrete cylinders at the age of 28 days. All specimens were made from the same materials at the same time, consequently direct comparisons may be made between any two sets of tests.

MATERIALS.

The portland cement used consisted of a mixture of equal parts of four brands purchased from Chicago dealers. The cement conformed to all the requirements of the Standard Specifications and Tests for Portland Cement of the American Society for Testing Materials.

In general the aggregates consisted of sand and pebbles from the Chicago Gravel Company's pit near Elgin, Ill. In one group of tests crushed limestone was used as coarse aggregate. Sieve analysis and miscellaneous tests of aggregates are given in Table 1.

The "fineness modulus" of an aggregate may be used as a measure of its size and grading. It is the sum of the percentages in the sieve analysis divided by 100. The sieve analysis is expressed in terms of weight or volume *coarser* than each sieve. Tyler standard screen scale sieves are used. The sizes of sieves and fineness moduli of the aggregates used in these tests are shown in Table 1. Low values of fineness modulus correspond to the small size and high values to the coarse sizes of the aggregate.*

TEST PIECES.

All test pieces consisted of 6 by 12-in. cylinders which were stored in damp sand for 28 days. The concrete for each specimen was proportioned separately and mixed by hand with a bricklayer's trowel in a shallow metal pan. The forms consisted of 12-in. lengths of cold-drawn

*For further details on fineness modulus of aggregates see the writer's report on "Design of Concrete Mixtures," Bulletin 1, Structural Materials Research Laboratory.

steel tubing, split along one element. Each form stood on a machined cast-iron base plate. A smooth top was formed by means of neat cement and plate glass.

Unless otherwise noted, the specimens were molded by the "standard" hand-puddling method before subjecting them to vibration, jigging or pressure. This method consists of puddling the fresh concrete in the metal form in 4-in. layers by means of 25 strokes with a 5/8-in. round steel bar and leveling off with a trowel. This method has been in use for

TABLE 1.—MISCELLANEOUS TESTS OF AGGREGATES.

Size	Kind	Weight lb. per cu. ft.	Density	Sieve Analysis of Aggregate (Per cent by weight coarser than each sieve.)									Fineness Modulus.**
				100	48*	28*	14*	8	4	⅜ in.	¾ in.	1½ in.	
0-28*	Elgin and Pebbles	102	0.61	88	42	0	..	..	..	..	..	..	1.20
0-14*		104	0.62	90	91	36	0	..	..	..	..	..	2.25
0-8		108	0.65	99	93	50	22	0	..	..	..	..	2.64
0-4		112	0.67	99	94	59	36	18	0	..	..	..	3.06
0-⅜ in.		120	0.72	99	96	73	57	46	33	0	..	..	4.04
0-¾ in.		124	0.74	99	97	82	72	64	58	30	0	..	5.02
0-1½ in.		128	0.77	99	98	87	80	75	68	48	20	0	5.75
0-1½ in.	Elgin Sand and Pebbles	119	0.71	99	95	69	51	38	24	17	7	0	4.00
		125	0.75	99	97	79	68	58	49	35	15	0	5.00
		126	0.76	99	98	85	76	69	62	43	18	0	5.50
		128	0.77	99	98	87	80	75	68	48	20	0	5.75
		128	0.77	100	98	90	84	79	75	52	22	0	6.00
		125	0.75	100	99	92	88	84	81	57	24	0	6.25
		120	0.72	100	99	95	92	90	87	62	25	0	6.50
0-1½ in.	Elgin Sand and Crushed Limestone	123	0.74	99	95	69	51	38	24	17	7	0	4.00
		128	0.77	99	97	79	68	58	49	35	15	0	5.00
		124	0.74	99	98	85	76	69	62	43	18	0	5.50
		122	0.73	99	98	87	80	75	68	48	20	0	5.75
		118	0.71	100	98	90	84	79	75	52	22	0	6.00
		114	0.68	100	99	92	88	84	81	57	24	0	6.25
		110	0.66	100	99	95	92	90	87	62	25	0	6.50

*(Note added at Second Printing, September, 1922.) The No. 48, 28, and 14-mesh sieves give the same separation as the No. 50, 30, and 16 now used in the "Tentative Method of Test for Sieve Analysis of Aggregates for Concrete" of the American Society for Testing Materials. The No. 50, 30, and 16 sieves are now used in all our tests.

**The sum of percentages in sieve analysis, divided by 100.

several years in our research work and has been found to give uniform results for different operators. The strength of the concrete produced by this method of molding is used as a basis for comparison (100 per cent) for all other methods of treatment included in this investigation.

The mixture is expressed as one volume of cement to a given number of volumes of mixed aggregate. A 1:5 mix expressed in this manner is about the same as the ordinary 1:2:4 mix. The exact equivalent of the latter will vary with the size and grading of the aggregates.

The water content of the concrete is expressed in terms of the relative consistency and the "water-ratio." A relative consistency of 1.00 (normal consistency) is of such plasticity that the concrete of usual mixes will give a slump of ½ to 1 in. if the metal form is withdrawn by a

steady upward pull immediately after molding the cylinder† by the standard method. A relative consistency of 1.10 contains 10 per cent more vater than normal consistency. The water-ratio is the ratio of volume of vater to volume of cement in the batch. The weight of cement was assimed as 94 lb. per cu. ft. For one mix and given concrete materials the rehtive consistency and water-ratio may be used interchangeably.



FIG. 1.—ELECTRIC VIBRATOR.

Shows set-up for vibration tests given in Table 3.
Motor weighed 12 lb., ran about 1000 r. p. m.

In the hand-molded specimens the method of placing the concrete was varied by changing the number of strokes of the puddling bar, using layers of different thickness, etc. Hand-tampers 2 in. and 5 in. in diameter were also used. In one set of tests the form was struck with a steel bar after molding by the standard puddling method.

†(Note added at Second Printing, September 1922.) Present practice in making the slump test for consistency or workability of concrete requires the use of a 4 by 8 by 12-in. truncated cone. For concrete of a given consistency the cone gives slumps about ½ less than the cylinder. The truncated cone is specified in the Progress Report of the Joint Committee on Standard Specifications for Concrete and Reinforced Concrete and is used in the Tentative Specifications for Workability of Concrete for Concrete Pavements of the American Society for Testing Materials.

In the vibration tests the cylinder mold was bolted to a light timber table and the concrete specimen molded by the standard hand-puddling method described above.

Violent vibration was produced by holding an electric motor frame against the side of the steel form as shown in Fig. 1. The motor carried an eccentric flywheel, weighed 12 lb. and ran about 1000 r. p. m. The time of vibration varied from 5 sec. to 1 min.

The jigging tests were made on the machine shown in Fig. 2. The machine consisted of a framework carrying a metal table about 4 ft. wide



FIG 2.—JIGGING MACHINE.

Steel table 4 by 8 ft.; weight 700 lb. Table raised by means of cams; rate and height of drop can be varied over wide range.

and 8 ft. long weighing about 700 lb. The table was raised by means of belt-driven cams on two longitudinal shafts. The rate and height of drop could be varied over a wide range. In most of the tests the machine was run for 20 sec. at 100 drops per min., 0.1-in. drop; however, each of these factors were varied with the other two constant.

All specimens were molded by the standard hand-puddling method before pressure was applied. Pressures up to 10 lb. per sq. in. were applied by piling weights on top of a loose-fitting cover plate. Pressures of 25 and 50 lb. per sq. in. were applied by weighted levers. Pressures of 100 to 500 lb. per sq. in. were obtained by placing the freshly molded specimen in a testing machine, as shown in Fig. 3. The spring facilitated maintaining a constant pressure. For all pressures the time of application varied from 15 min. to 16 hr.

The metal forms are fairly tight and permit little leakage of water under ordinary conditions. For the wetter concretes the joints were sealed with paraffin. In the pressure tests the water expelled was collected by means of sponges and weighed. It should be noted that this water was almost clear.

Test cylinders were made in sets of 5 on different days. One specimen of each form was made before starting the second round. The strengths given in the tables are the average of 5 entirely independent

tests. In this way minor variations in materials, proportions, manipulation, etc., are eliminated. In the case of the "standard" hand-puddled specimens were made in different parts of the series.

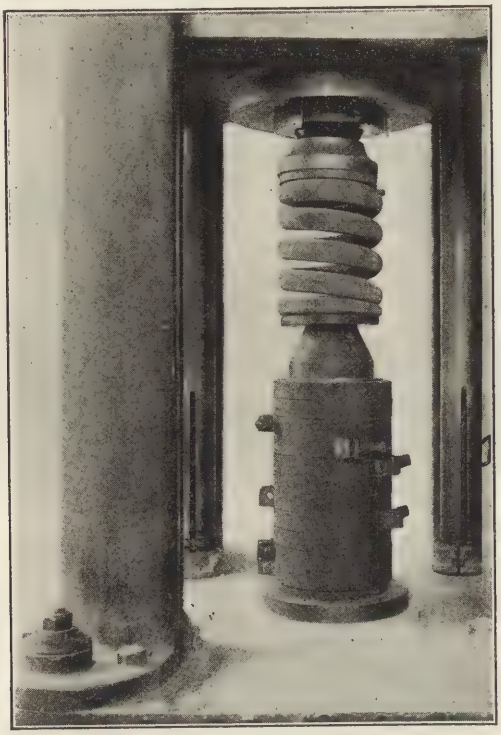


FIG. 3.—METHOD OF APPLYING PRESSURE TO FRESH CONCRETE.

The higher pressures were applied by means of a testing machine. The spring facilitated maintaining a constant pressure. The plate in contact with fresh concrete was loose-fitting. The water expelled from concrete was collected by means of sponges and weighed.

TEST DATA AND DISCUSSION.

Data of the tests will be found in Tables 2 to 7. Only average values are reported. It will be noted that the "standard" hand-puddled concrete (average of 15 tests) is used as the basis of comparison. The diagrams in Figs. 4 to 16 give the data in graphical form.

A comparison of the relative effects of puddling 1:5 plastic concrete with a steel bar and tamping with tampers of different weight and size is given in Table 2.

TABLE 2.—EFFECT OF METHOD OF MOLDING CONCRETE SPECIMENS.

Compression tests of 6 by 12-in. cylinders.
Mix 1 : 5 by volume.
Relative consistency, 1.00; water ratio, 0.87.
Age at test 28 days; stored in damp sand; tested damp.
Aggregate—sand and pebbles from Elgin, Ill., graded 0-1½ in.; fineness modulus, 5.75.
Each value is the average of 5 tests made on different days.

Ref. No.	Treatment of Concrete	Compressive Strength	
		lb. per sq. in.	Per cent of Standard
1	12 strokes around perimeter of form for each 4-in. layer of concrete using ⅝-in. steel bar.	2680	96
31	25 strokes distributed over section for each 4-in. layer using ⅝-in. steel bar. (Standard method.)	2800	
51		2710	
84		2840	100
		2780*	
2	50 strokes distributed over section for each 4-in. layer using ⅝-in. bar.	2810	101
147	12 strokes on each 3-in. layer using 2-lb. tamper 2 in. in diameter.	2690	97
148	12 strokes on each 6-in. layer, using 2-lb. 2-in. tamper.	2420	87
149	12 strokes on first 3-in. layer using 2-lb. 2-in. tamper, forms then filled before tamping again with 12 strokes.	2430	87
150	12 strokes on first 3-in. layer, using 2-lb. 2-in. tamper, remaining concrete settled by tapping form lightly.	2500	90
3	25 strokes distributed over section for each 4-in. layer with 2-lb. 2-in. tamper.	2800	101
4	25 strokes distributed over section for each 4-in. layer with 2-lb. 5-in. tamper.	2570	92
5	Standard method of molding, except form struck 3 light blows with steel bar after puddling each 4-in. layer.	2740	98

*Average of 15 tests made on different days. This value is used as a basis for comparison in Tables 2, 3, 6 and 7.

The effect of vibration with electric vibrator is shown in Table 3 and Fig. 4. Vibrating for about 30 seconds caused no appreciable effect on the strength of concrete which had been puddled in place by hand. The tests indicate that hand-puddling (if thoroughly done) is just as effective as vibration in placing concrete. In other words, concrete which completely fills the form is not improved by vibration. This should not be construed as meaning that vibration is not effective in causing concrete to find its way into intricate form work and around the reinforcing bars.

The effect of jigging is shown in Tables 4 to 6, and Fig. 5 to 12. The jigging method used was one which would be applicable to concrete products plants. The tests show that in general jigging of concrete which has been placed by puddling is injurious to the strength. The improvement for the small-sized aggregates is probably due to the fact that the puddling method is not so satisfactory for this condition.

In comparing the tests of crushed limestone and pebbles in Table 5 it should be noted that the three coarsest gradings in each group (fineness

TABLE 3.—EFFECT OF VIBRATION WITH ELECTRIC MOTOR.

Method of vibrating shown in Fig. 1.
Compression tests of 6 by 12-in. cylinders.
Mix, 1:5 by volume.
Age at test 28 days; stored in damp sand; tested damp.
Aggregate—sand and pebbles from Elgin, Ill., graded 0-1½ in.; fineness modulus, 5.75.
Each value is the average of 5 tests made on different days.
Results of tests are platted in Fig. 4.

Ref. No.	Treatment of Concrete	Compressive Strength	
		lb. per sq. in.	Per cent of Standard
31, 51, 84	Standard method of molding.	2780*	100
6	Standard method of molding, vibrated 5 sec.	2880	104
7	Standard method of molding, vibrated 10 sec.	2640	95
8	Standard method of molding, vibrated 20 sec.	2830	102
9	Standard method of molding, vibrated 30 sec.	2700	97
10	Standard method of molding, vibrated 45 sec.	2520	91
11	Standard method of molding, vibrated 60 sec.	2470	89

*Average of 15 tests made on different days, See Table 2.

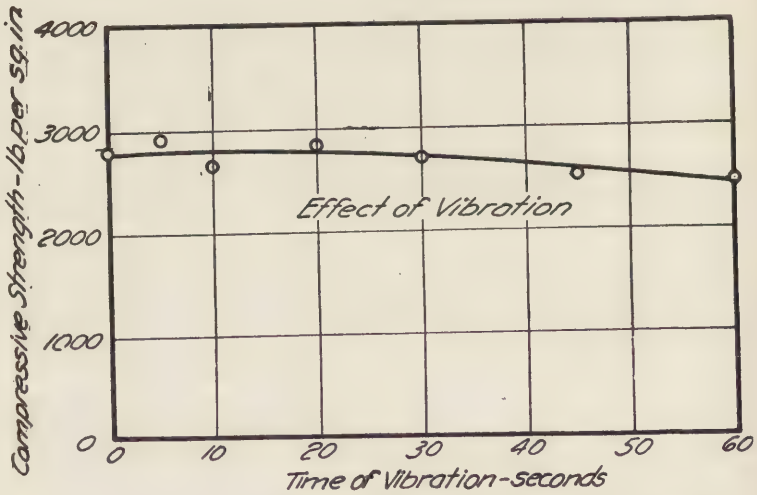


FIG. 4.—EFFECT OF VIBRATION ON THE STRENGTH OF CONCRETE.

Vibration produced by electric motor shown in Fig. 1. Compression tests of 6 by 12-in. cylinders. Age, 28 days. Data from Table 3.

TABLE 4.—EFFECT OF JIGGING ON THE STRENGTH OF CONCRETE.

(Concrete of Different Mixes and Consistencies.)

All cylinders were molded by the standard method before vibrating on machine shown in Fig. 2. (100 r.p.m.; 0.1-in. drop; jigged 20 sec.)

Compression tests of 6 by 12-in. cylinders.

Aggregates, sand and pebbles from Elgin, Ill., graded 0-1½-in.; fineness modulus, 5.75.

Age at test 28 days; stored in damp sand; tested damp.

Each value is the average of 5 tests made on different days.

Values platted in Fig. 5.

Ref. No.	Mix by Vol.	Relative Consistency	Water-Ratio to Volume of Cement	Compressive Strength		
				Standard Method lb. per sq. in.	Standard Method Plus Jigging, lb. per sq. in.	Jigged Concrete, Per cent of Standard
75	1:7	0.70	0.757	1270	1560	123
76	...	0.80	0.866	1650	1910	116
77	...	0.90	0 974	1730	2000	116
78	...	1.00	1.081	1710	1800	105
79	...	1.10	1.190	1480	1460	99
80	...	1.25	1.353	1140	1110	97
				Av. 1500	1640	109
81	1:5	0.70	0.612	1650	2020	122
82	...	0.80	0.700	2560	2870	112
83	...	0.90	0.788	2920	3120	107
84	...	1.00	0.875	2840	2630	93
85	...	1.10	0.962	2120	2040	96
86	...	1.25	1.085	1580	1560	99
				Av. 2280	2370	104
87	1:4	0.70	0.540	1690	2160	128
88	...	0.80	0.618	3760	3600	96
89	...	0.90	0.695	3750	3710	99
90	...	1.00	0.777	3510	3190	91
91	...	1.10	0.849	2890	2520	87
92	...	1.25	0.965	1880	1750	93
				Av. 2910	2820	97
93	1:3	0.70	0.469	2160	2640	122
94	...	0.80	0.536	4050	4410	109
95	...	0.90	0.603	4530	4800	106
96	...	1.00	0.670	4050	3920	97
97	...	1.10	0.737	3420	3470	101
98	...	1.25	0.838	2680	2420	90
				Av. 3480	3610	104

TABLE 5.—EFFECT OF JIGGING ON THE STRENGTH OF CONCRETE.

(Using Aggregates of Different Size and Grading.)

Values from tests platted in Fig. 7 and 8.

All cylinders were molded by the standard method before jigging on machine shown in Fig. 2. (100 r.p.m.; 0.1-in. drop; jigged 20 sec.)

Compression tests of 6 by 12-in. cylinders.

Age at test 28 days; stored in damp sand; tested damp.

Aggregates—sand and pebbles from Elgin, Ill., except where otherwise noted.

Each value is the average of 5 tests made on different days.

Variation in grading in last two groups was produced by mixing different percentages of sand and coarse aggregate.

Ref. No.	Mix by Vol.	Aggregate		Relative Consistency	Water-Ratio to Volume of Cement	Compressive Strength		
		Size	F. M.			Standard Method, lb. per sq. in.	Standard Method Plus Jigging, lb. per sq. in.	Jigged Concrete, Per cent of Standard
123	1:5	0–28	1.20	1.00	1.410	360	400	111
124	...	0–14	2.25	....	1.290	510	580	114
125	...	0–8	2.64	....	1.245	500	650	130
126	...	0–4	3.06	....	1.195	950	1060	112
127	...	0–$\frac{3}{8}$	4.04	....	1.080	1540	1270	82
128	...	0–$\frac{3}{4}$	5.02	....	0.960	2290	2060	90
84	...	0–1$\frac{1}{2}$	5.75	....	0.875	2840	2630	93
129	1:3	0–28	1.20	1.00	0.990	680	860	126
130	...	0–14	2.25	....	0.920	1060	1360	128
131	...	0–8	2.64	....	0.890	1520	1720	113
132	...	0–4	3.06	....	0.860	2080	2020	97
133	...	0–$\frac{3}{8}$	4.04	....	0.790	3050	2930	96
134	...	0–$\frac{3}{4}$	5.02	....	0.720	3840	3420	89
96	...	0–1$\frac{1}{2}$	5.75	....	0.670	4050	3920	97
47	1:5	0–1$\frac{1}{2}$	4.00	1.00	1.085	1450	1460	101
48	...	....	5.00	....	0.960	2160	1960	91
49	...	....	5.50	....	0.910	2500	2250	90
50	...	....	5.75	....	0.875	2980	2360	79
51	...	....	6.00†	....	0.845	2710	2630	97
52	...	....	6.25†	....	0.810	2610	2520	96
53	...	....	6.50†	....	0.785	2110	2010	95
54*	1:5	0–1$\frac{1}{2}$	4.00	1.00	1.085	1180	1390	118
55*	...	....	5.00	....	0.960	2030	1850	91
56*	...	....	5.50	....	0.910	2450	2290	93
57*	...	....	5.75	....	0.875	2630	2430	92
58*	...	....	6.00†	....	0.845	2420	2500	103
59*	...	....	6.25†	....	0.810	1960	1760	90
60*	...	....	6.50†	....	0.785	1550	1460	94

* Crushed limestone for coarse aggregate.

† These aggregates are too coarse for the quantity of cement used. See discussion on page 15 also Bulletin 1, "Design of Concrete Mixtures," Structural Materials Research Laboratory.

TABLE 6.—EFFECT OF JIGGING ON THE STRENGTH OF CONCRETE.

All cylinders were molded by the standard method before jigging on machine shown in Fig. 2.
Compression tests of 6 by 12-in. cylinders.
Age at test 28 days; stored in damp sand; tested damp.
Aggregates—sand and pebbles from Elgin, Ill. (graded 0–1½ in.).
Each value is the average of 5 tests made on different days.

Ref. No.	Mix by Volume	F. M. of Aggregate	Relative Consistency	Water-Ratio to Volume of Cement	Compressive Strength		Treatment of Concrete
					lb. per sq. in.	Per cent of Standard	
Effect of Height of Drop, 100 r.p.m., for 20 sec. (See Fig. 9).							
31, 51, 84	1:5	5.75	1.00	0.875	2780*	100	Standard method of molding.
17	...	....	....	.....	2340	84	Drop .02 in.
18	...	....	....	.....	2480	89	Drop .05 in.
19	...	....	....	.....	2250	81	Drop .10 in.
20	...	....	....	.....	2520	91	Drop .20 in.
21	...	....	....	.....	2640	95	Drop .30 in.
22	...	....	....	.....	2460	88	Drop .50 in.
Effect of Rate of Jigging, 0.1-in. drop, for 20 sec. (See Fig. 10).							
31, 51, 84	1:5	5.75	1.00	0.875	2780*	100	Standard method of molding.
12	...	....	....	.....	2640	95	Jigged at 30 r.p.m.
13	...	....	....	.....	2490	90	Jigged at 50 r.p.m.
14	...	....	....	.....	2470	89	Jigged at 75 r.p.m.
15	...	....	....	.....	2520	91	Jigged at 100 r.p.m.
16	...	....	....	.....	2420	87	Jigged at 150 r.p.m.
Effect of Time Jigged at 100 r.p.m., 0.1-in. drop (See Fig. 11).							
13, 51, 84	1:5	5.75	1.00	0.875	2780*	100	Standard method of molding.
32	...	....	....	....	2440	88	Jigged for 5 sec.
33	...	....	....	....	2260	81	Jigged for 10 sec.
34	...	....	....	....	2390	86	Jigged for 20 sec.
35	...	....	....	....	2320	83	Jigged for 30 sec.
36	...	....	....	....	2251	81	Jigged for 45 sec.
37	...	....	....	....	2190	79	Jigged for 1 min.
38	...	....	....	....	2090	75	Jigged for 2 min.
39	...	....	....	....	2170	78	Jigged for 3 min.
Miscellaneous Jigging Tests, 100 r.p.m., 0.1-in. drop, jigged 20 sec. (See Fig. 12).							
31, 51, 84	1:5	5.75	1.00	0.875	2780*	100	Standard method of molding.
40	...	....	....	....	2780	100	Standard method of molding, jigged with 30-lb. weight on top. (See Figs. 9, 10 and 11.)
15, 19, 34	...	....	....	....	2390	86	Jigged immediately.
41	...	....	....	....	2550	92	Stood 1 hr. before jigging.
42	...	....	....	....	2940	106	Stood 2 hr. before jigging.
43	...	....	....	....	2950	106	Stood 3 hr. before jigging.
44	...	....	....	....	3000	108	Stood 4 hr. before jigging.
45	...	....	....	....	2870	103	Stood 6 hr. before jigging.
46	...	....	....	....	2770	100	Molded by standard method on jigging machine while in operation.

* Average of 15 tests made on different days. See Table 2.

TABLE 7.—EFFECT OF PRESSURE ON THE STRENGTH OF CONCRETE.

All cylinders were molded by standard method before pressure was applied. Pressures higher than 50 lb. per sq. in. were applied by a testing machine, as shown in Fig. 3.

Ref. No.	Mix by Volume	F. M. of Agg.	Relative Consistency	Water-Ratio		Compressive Strength		Treatment of Concrete
				As Mixed	After Pressure	lb. per sq. in.	Per cent of Standard	
Pressure Applied 15 Minutes.								
31, 51, 84	1:5	5.75	1.00	0.875	0.875	2780*	100	Standard method of molding
23	...	....	....	.....	0.842	3140	113	Pressure, 2 lb. per sq. in.
24	...	....	....	.....	0.845	3000	108	" 5 lb. per sq. in.
25	...	....	....	.....	0.831	2930	105	" 10 lb. per sq. in.
26	...	....	....	.....	0.816	2900	104	" 25 lb. per sq. in.
27	...	....	....	.....	0.820	3130	113	" 50 lb. per sq. in.
28	...	....	....	.....	0.810	3470	125	" 100 lb. per sq. in.
29	...	....	....	.....	0.785	3360	121	" 200 lb. per sq. in.
30	...	....	....	.....	0.751	3590	129	" 500 lb. per sq. in.
				Av.	0.819	3150	113	
Pressure Applied 1 Hour.								
31, 51, 84	1:5	5.75	1.00	0.875	0.875	2780*	100	Standard method of molding
23	...	....	....	.....	0.845	2920	105	Pressure, 2 lb. per sq. in.
24	...	....	....	.....	0.824	2830	102	" 5 lb. per sq. in.
25	...	....	....	.....	0.839	2950	106	" 10 lb. per sq. in.
26	...	....	....	.....	0.834	2880	104	" 25 lb. per sq. in.
27	...	....	....	.....	0.821	3120	112	" 50 lb. per sq. in.
28	...	....	....	.....	0.810	3190	115	" 100 lb. per sq. in.
29	...	....	....	.....	0.781	3790	136	" 200 lb. per sq. in.
30	...	....	....	.....	0.756	3470	125	" 500 lb. per sq. in.
				Av.	0.820	3100	112	
Pressure Applied 4 Hours.								
31, 51, 84	1:5	5.75	1.00	0.875	0.875	2780*	100	Standard method of molding.
23	...	....	....	.....	0.855	2880	104	Pressure, 2 lb. per sq. in.
24	...	....	....	.....	0.845	2980	107	" 5 lb. per sq. in.
25	...	....	....	.....	0.820	3200	115	" 10 lb. per sq. in.
26	...	....	....	.....	0.840	2900	104	" 25 lb. per sq. in.
27	...	....	....	.....	0.821	2990	108	" 50 lb. per sq. in.
28	...	....	....	.....	0.795	3270	118	" 100 lb. per sq. in.
29	...	....	....	.....	0.767	3350	121	" 200 lb. per sq. in.
30	...	....	....	.....	0.750	3680	132	" 500 lb. per sq. in.
				Av.	0.819	3120	112	
Pressure Applied 16 Hours.								
31, 51, 84	1:5	5.75	1.00	0.875	0.875	2780*	100	Standard method of molding.
23	...	....	....	.....	0.834	3060	110	Pressure, 2 lb. per sq. in.
24	...	....	....	.....	0.824	2710	97	" 5 lb. per sq. in.
25	...	....	....	.....	0.815	2630	95	" 10 lb. per sq. in.
26	...	....	....	.....	0.846	2670	96	" 25 lb. per sq. in.
27	...	....	....	.....	0.798	3320	119	" 50 lb. per sq. in.
28	...	....	....	.....	0.795	3330	120	" 100 lb. per sq. in.
29	...	....	....	.....	0.794	3410	123	" 200 lb. per sq. in.
30	...	....	....	.....	0.766	3420	123	" 500 lb. per sq. in.
				Av.	0.816	3040	109	
Grand Average of all Times of Application of Pressure (See Figs 13 to 16).								
31, 51, 84	1:5	5.75	1.00	0.875	0.875	2780*	100	Standard method of molding.
.....	...	....	....	.....	0.844	3000	108	Pressure, 2 lb. per sq. in.
.....	...	....	....	.....	0.834	2880	104	" 5 lb. per sq. in.
.....	...	....	....	.....	0.826	2930	105	" 10 lb. per sq. in.
.....	...	....	....	.....	0.834	2840	102	" 25 lb. per sq. in.
.....	...	....	....	.....	0.815	3140	113	" 50 lb. per sq. in.
.....	...	....	....	.....	0.802	3320	119	" 100 lb. per sq. in.
.....	...	....	....	.....	0.782	3480	125	" 200 lb. per sq. in.
.....	...	....	....	.....	0.756	3540	127	" 500 lb. per sq. in.

* Average of 15 tests made on different days, see Table 2.

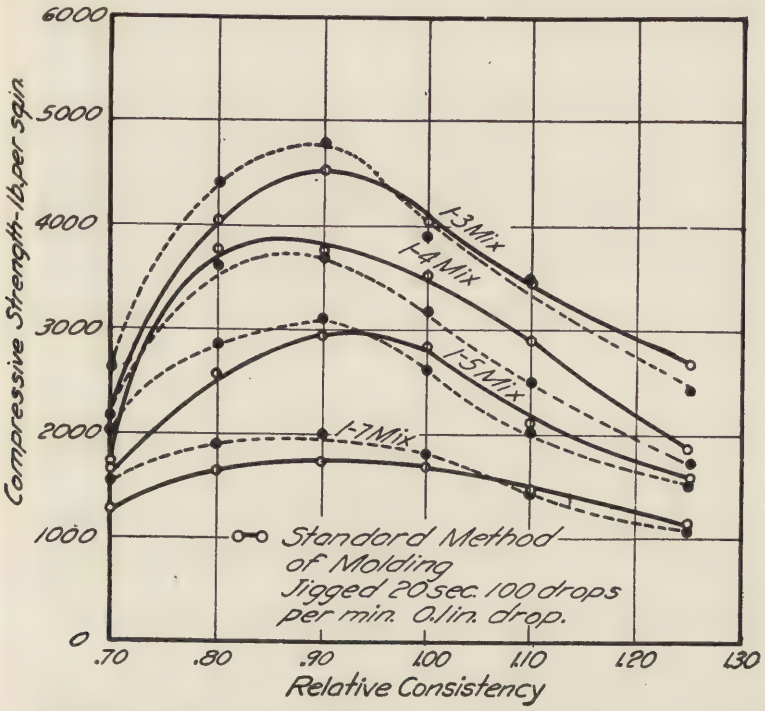


FIG. 5.—EFFECT OF CONSISTENCY ON THE STRENGTH OF JIGGED CONCRETE.

Specimens molded by standard method and parallel sets jigged on machine shown in Fig. 2. Compression tests of 6 by 12-in. cylinders. Age 28 days. Data from Table 4.

modulus 6.00 and over) are too coarse for this mix, consequently the concrete strengths fall off. The extremely coarse mixtures cause a much greater reduction in the strength of the concrete made from crushed stone than from gravel. For this reason it is not proper to draw conclusions from a comparison of average values from the two types of coarse aggregate. If we confine our attention to the ordinary range in aggregate grading (fineness modulus 5.00 to 5.75) we find little difference in strength of concrete from the two materials. For these conditions the average strength with pebbles is 2550 lb. per sq. in. for the standard method of hand-puddling and 2190 after jigging; corresponding values for crushed stone are 2370 and 2190 lb. per sq. in.

The tests of concrete setting under pressure are of interest in that they reveal the reason for increased strength due to this treatment. The concrete strength is increased due to the fact that some of the original

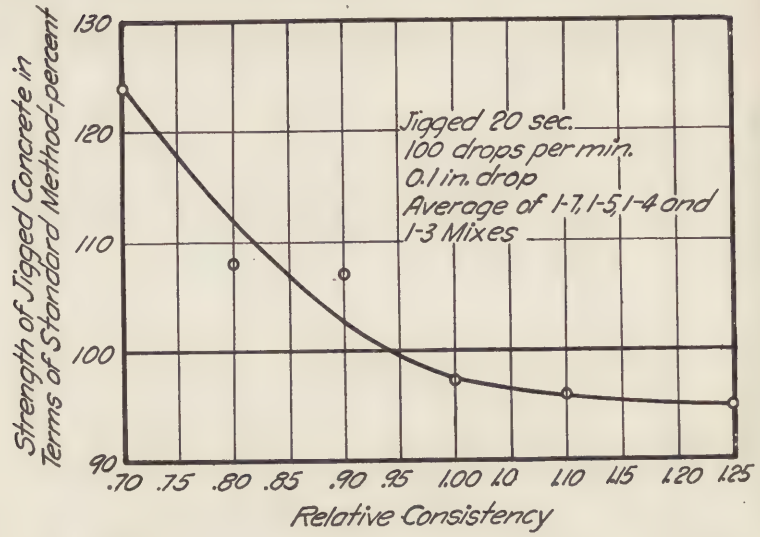


FIG. 6.—EFFECT OF CONSISTENCY ON THE STRENGTH OF JIGGED CONCRETE.

Each value is the average of 20 tests, 5 each from 4 different mixes in Table 4.

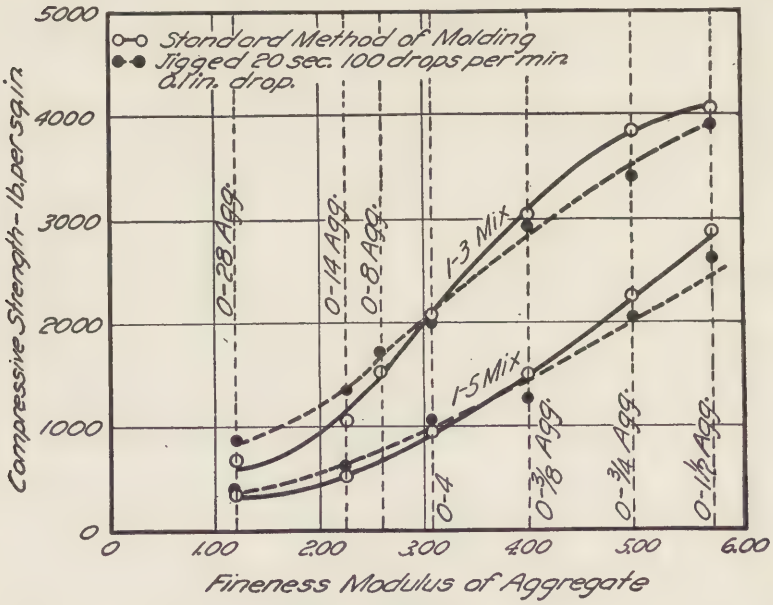


FIG. 7.—EFFECT OF SIZE OF AGGREGATE ON THE STRENGTH OF JIGGED CONCRETE.

Compression tests of 6 by 12-in. cylinders. Age 28 days. Data from Table 5.

mixing water is forced out. The higher the pressure, the more water is removed, hence the higher the strength.

Attention is called to the unusual uniformity of the results of the tests in this series, as illustrated by the fact that in the diagrams the points fall on smooth curves; in only a few instances is there an appreciable deviation from this rule.

SUMMARY AND CONCLUSIONS.

The tests gave conclusive results on many phases of the effect of vibration, jigging and pressure. In some instances the effect is entirely different from what accepted opinion would suggest. Following is a brief summary:

Effect of Puddling and Tamping.

1. Varying the number of strokes from 12 to 50 on each 4-in. layer in the standard method of hand-puddling with a 5/8-in. bar had little influence on the compressive strength of ordinary plastic concrete.

2. In general, the tamping methods used gave lower strengths than hand-puddling.

3. A tamper of large diameter for a given weight was less effective than one of small diameter.

4. Increasing the thickness of the layer from 4 to 6 in. caused a falling-off in strength of about 12 per cent for tamped concrete.

5. Tamping or puddling the first 4-in. layer only, caused a falling off in strength of 10 to 13 per cent.

6. Striking the metal form with a steel bar after the completion of molding by standard method had no effect on the strength of concrete.

7. The "standard" method of hand-puddling using 25 strokes with a 5/8-in. steel bar for each 4-in. layer of concrete in a 6 by 12-in. cylinder is recommended for laboratory tests of concrete.

Effect of Vibration with Electric Hammer.

8. Vibration of the specimen after molding by means of an electric hammer running at 1000 r. p. m. had little influence on the strength of the puddled concrete up to a period of about 30 seconds. If continued, there was a steady falling off in strength; after 45 to 60 seconds the strength was only 90 per cent of that produced by the standard method of puddling. (Table 3, and Fig. 4.)

Effect of Jigging.

9. In general, jigging in any manner with the apparatus used reduced the compressive strength of the concrete regardless of the height of drop, rate or duration of treatment. Exceptions were found in the dry mixes and those made of aggregates of the smaller sizes. (Tables 4 to 6; Fig. 5 to 12.)

10. There was little difference in the effect of jigging due to the quantity of cement used. (Fig. 5.)

11. In the very dry mixes the strength, due to jigging for 20 seconds, was increased about 25 per cent. (Fig. 5 and 6.)

12. The wetter mixes (relative consistency 1.10 to 1.25) were reduced in strength 3 to 6 per cent by jigging. (Fig. 5 and 6.)

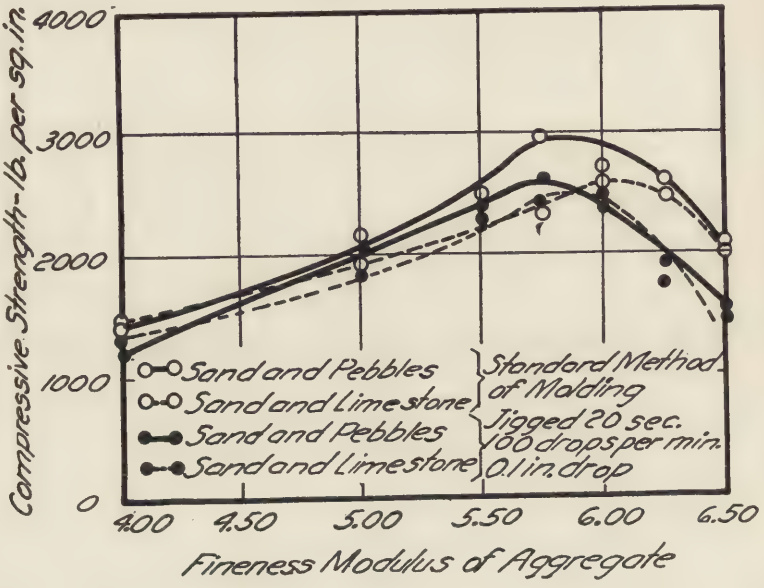


FIG. 8.—EFFECT OF GRADING OF AGGREGATE ON THE STRENGTH OF JIGGED CONCRETE.

Specimens molded by standard method and parallel sets jigged on machine shown in Fig. 2. Compression tests of 6 by 12-in. cylinders. 1:5 mix. Age, 28 days. All aggregate graded 0-1½ in. Data from Table 5.

13. Pebbles and crushed limestone as coarse aggregate gave essentially the same results in the jigging tests. (Fig. 8.)

14. The concretes from the finer aggregates showed a material increase in strength with jigging in both 1:5 and 1:3 mixes. (Fig. 7.)

15. For aggregate coarser than about ⅜-in., jigging reduced in strength from 3 to 10 per cent. (Fig. 7.)

16. The grading of the aggregates (for a given maximum size) had little influence on the effect of jigging. (Fig. 8.)

17. The greater the drop the greater the reduction in strength for 1:5 concrete. For a drop of ½-in. the strength was reduced 12 per cent. (Fig. 9.)

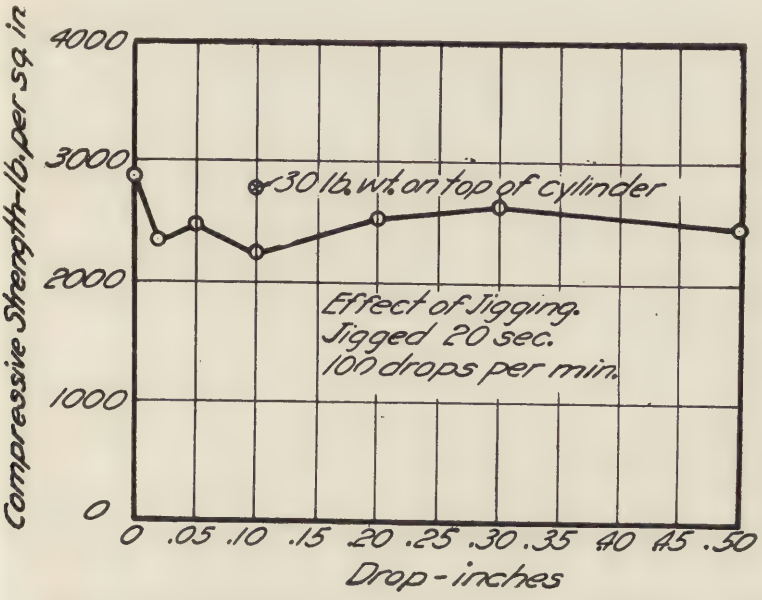


FIG. 9.—EFFECT OF HEIGHT OF DROP IN JIGGING TESTS.
Compression tests of 6 by 12-in. cylinders. Age 28 days. Data from Table 6.

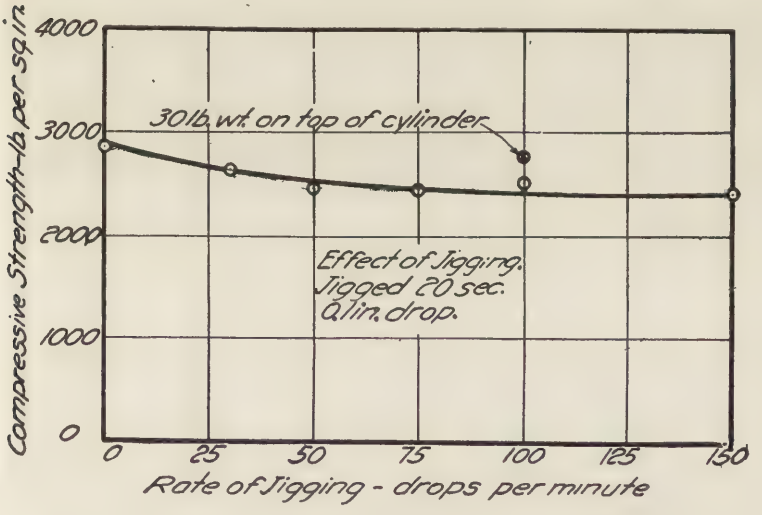


FIG. 10.—EFFECT OF RATE OF JIGGING ON THE STRENGTH OF CONCRETE.
Compression tests of 6 by 12-in. cylinders. 1:5 mix. Age 28 days. Data from Table 6.

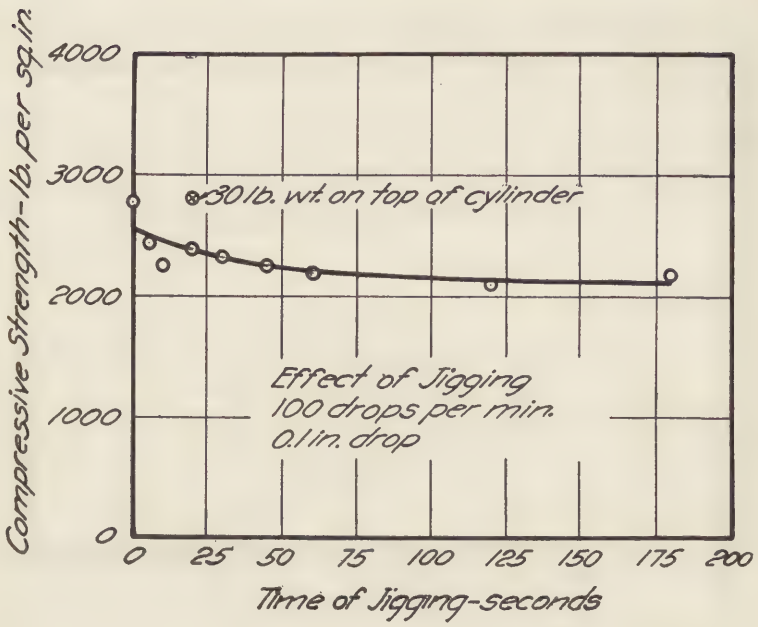


FIG. 11.—EFFECT OF DURATION OF JIGGING ON THE STRENGTH OF CONCRETE.

Compression tests of 6 by 12-in. cylinders. 1:5 mix. Age 28 days. Data from Table 6.

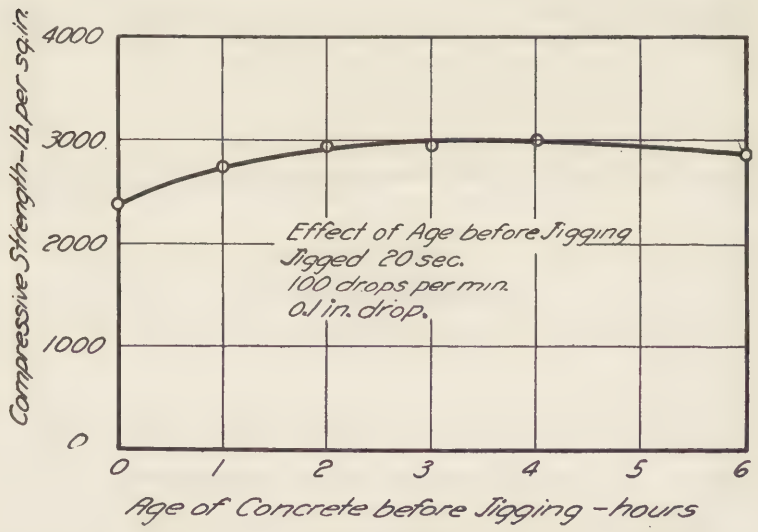


FIG. 12.—EFFECT OF AGE OF CONCRETE BEFORE JIGGING.

Compression tests of 6 by 12-in. cylinders. 1:5 mix. Age 28 days. Data from Table 6.

18. The faster the rate of jigging the lower the strength of 1:5 concrete. Using 1½-in. aggregate at 150 r. p. m., the strength was reduced about 13 per cent. (Fig. 10.)

19. The strength of 1:5 concrete fell off rapidly with the duration of jigging. After 2 to 3 minutes' jigging the strength was reduced about 20 per cent as compared with standard method of hand-puddling. (Fig. 11.)

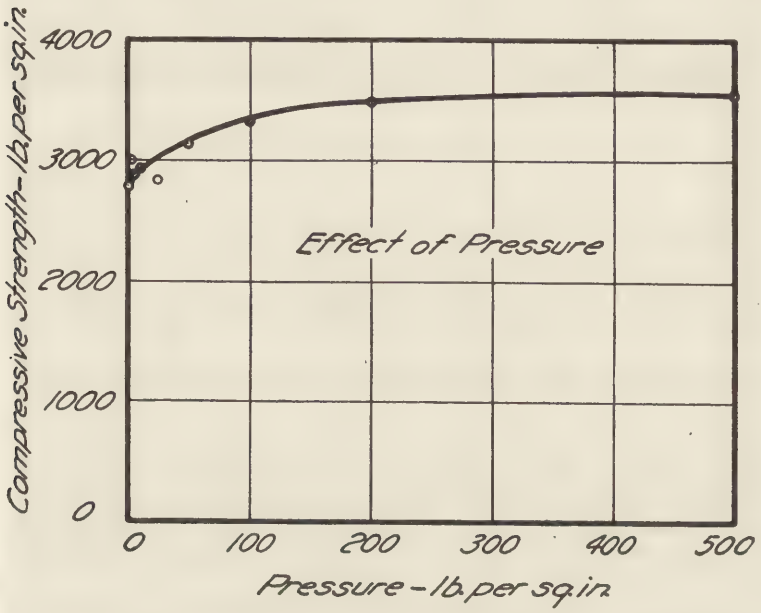


FIG. 13.—EFFECT OF PRESSURE ON THE STRENGTH OF CONCRETE.

Compression tests of 6 by 12-in. cylinders. 1:5 mix. Age, 28 days. Pressure applied immediately after molding. Each point represents the average of 20 tests, 5 each from 4 different times of application of pressure ranging from 15 min. to 16 hr. Data from Table 7.

20. Allowing the concrete to stand for a period of time before jigging, increased the strength to a slight extent. The maximum increase was found at 2 to 4 hr. (Fig. 12.)

21. The application of a pressure of 1 lb. per sq. in. during the jigging process (equivalent to a head of 1 ft. of fresh concrete) gave the same strength as standard hand-puddling. (Fig. 9, 10 and 11.)

22. Molding the cylinders by the standard method on the jigging table while it was in motion, gave the same strength as standard hand-puddling without jigging. (Table 6.)

Here the strength was reduced 13 per cent due to failure to tamp or puddle the top 9 in. of the cylinder. It is impracticable to duplicate in a compression test piece the performance of air hammers and other similar methods of vibrating when used on reinforced concrete work.

The tests show that with jigging high strength may be secured with drier mixes than would be feasible otherwise. It is a matter of common experience that concrete of drier consistency (and consequently higher strength) can be placed by means of jigging or vibration than would be possible by the usual methods.

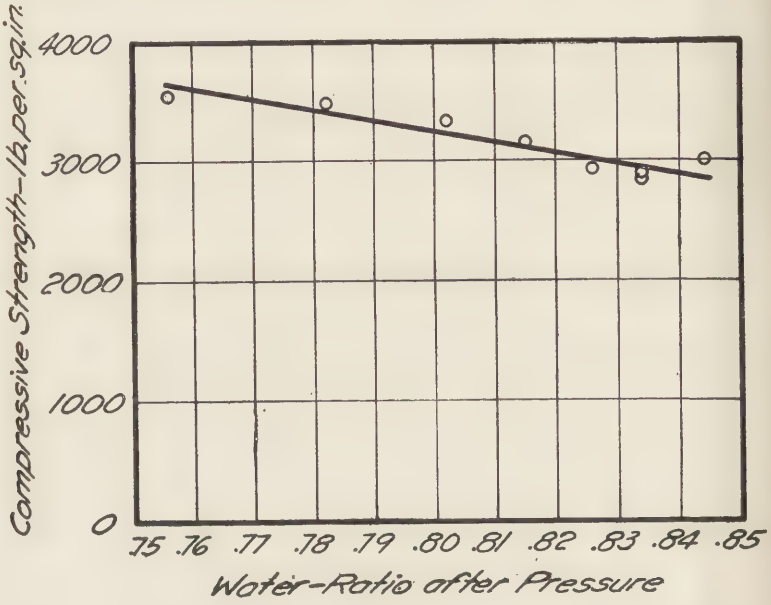


FIG. 16.—EFFECT OF QUANTITY OF MIXING WATER ON THE STRENGTH OF CONCRETE.

Compression tests of 6 by 12-in. cylinders. Age, 28 days. Water-ratio determined after application of pressure. Each point represents the average of 45 tests, 5 each from 9 different pressures. Data from grand average values in Table 7. The narrow range in water-ratio gives a straight line relation for these tests. The water-strength relation is represented by a curved line as shown in Bulletin 1, Structural Materials Research Laboratory.

The roller method of finishing concrete roads, walks and floors is an interesting example of a combination of slight vibration and pressure accompanied by the removal of excess water. Transverse tests on concrete made in this Laboratory showed a marked increase in strength of the rolled slabs as compared with similar slabs without rolling.*

*See paper of A. N. Johnson, Proc. Am. Soc. Testing Mat., 1917, Part II, p. 378.

It is clear from these tests that if tamping, vibration or pressure on fresh concrete are to be effective in increasing its strength three factors must be kept in mind:

(1) We must take advantage of the fact that with these methods the concrete can be placed and finished drier than with ordinary methods.

(2) Excess water which is brought to the surface must be removed.

(3) We must take advantage of the fact that aggregate of a coarser grading may be used when such methods are employed than would be practicable otherwise.

The advantages to be gained under (3) are due to the fact that up to a certain point a plastic mix can be secured with a smaller quantity of water if the aggregate is as coarse as practicable. Unless these precautions are taken, tamping and vibration are of doubtful value.

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Bulletin 4

Structural Materials Research Laboratory
Lewis Institute
Chicago

Effect of Fineness of Cement

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FOREWORD TO REVISED EDITION

This report was originally published in the copyrighted Proceedings of the American Society for Testing Materials, Vol. XIX, Part II, 1919. Acknowledgment is made to the Society for permission to reprint the paper in bulletin form.

The oral and written discussions which appeared in the Proceedings are omitted from this Bulletin.

In issuing this revised edition, only a few minor editorial changes have been made in the text and no change in the figures. Tables 17, 24, 26, 28, and 29, have been revised to include 1-year tests of mortar and concrete in Series 120. No changes in the original discussion or the general conclusions have been made necessary by the new tests. Without exception the 1-year tests gave higher values than at 3 months.

The following bibliographies have been added:

Effect of Fineness of Cement;

Methods of Measuring Fineness of Cement and Other Powdered Materials.

EFFECT OF FINENESS OF CEMENT

By Duff A. Abrams.

SUMMARY.

The recent revision of the Standard Specifications for Portland Cement served to focus the attention of engineers on the function of fineness of grinding of cement in producing concrete of high strength and other desirable properties. An investigation of this subject has been under way at Lewis Institute for the past 4 years. Five series of tests have been completed; another series, now under way, is not included in this report. These studies were made as a part of the investigations of concrete and concrete materials being carried out through the cooperation of the Portland Cement Association and Lewis Institute at the Structural Materials Research Laboratory.

The portland cements used were from 7 commercial mills. These plants represent the principal cement-producing districts east of the Mississippi River. Fifty-one different samples of cement were used. The cements were ground at the mill to 4 to 7 degrees of fineness, which gave residues ranging from 2 to 43 per cent on the standard No. 200 sieve. In general, the aggregate consisted of sand and pebbles; in one series blast-furnace slag and a light-weight aggregate consisting of burnt shale were used.

This report covers compression tests on 6125 6 by 12-in. concrete cylinders, 9000 compression and tension tests of mortar, and several thousand miscellaneous tests. Strength tests of concrete and mortar were made at ages of 7 days to 1 year.

Definite information has been secured on the following:

(*a*) Effect of fineness of cement on the strength of concrete;
(*b*) Quality of concrete using different cements;
(*c*) Effect of the quantity of cement used;
(*d*) Effect of consistency of the concrete;
(*e*) Effect of size and grading of the aggregate;
(*f*) Variation in the type of aggregate;
(*g*) Effect of age of concrete;
(*h*) Elongation and contraction of concrete;
(*i*) Effect of fineness of cement on workability of concrete.

The following are the principal conclusions from the tests:

1. There is no necessary relation between the strength of concrete and the fineness of the cement, if different cements are considered.

2. In general, the strength of concrete increases with the fineness of a given lot of cement, for all mixes, consistencies, gradings of the aggregate, and ages of concrete. The cements with residues lower than about 10 per cent were inclined to give erratic results in the strength tests; one lot showed an abnormal increase, and two a pronounced decrease in strength as compared with the other tests on coarser cements in the same lot.

3. For residues higher than 10 per cent the strength of concrete varies approximately inversely as the residue on the No. 200 sieve.

4. Fine grinding of cement is more effective in increasing the strength of lean mixtures than rich ones.

5. Fine grinding of cement is more effective in increasing the strength of concrete at 7 days than at ages of 28 days to 1 year.

6. For the usual range of consistencies the effect of fineness of cement is independent of the consistency of the concrete. The rate of increase in strength with fineness is lowered for very wet mixtures.

7. Ordinary concrete mixtures at 28 days show an increase in strength of about 2 per cent for each 1 per cent reduction in the residue of the cement on the No. 200 sieve. At 7 days, 3 months and 1 year the corresponding increases in strength are about 2.5, 1.7 and 1.4 per cent.

8. The decreased benefit of fine grinding of cement with the age of the concrete does not bear out accepted opinion that the coarser particles of cement do not hydrate, but indicates that the principal result of finer grinding is to hasten the early hardening of the concrete.

9. For the richer mixtures and the consistency necessary for building construction, the fineness of the cement has no appreciable effect on the workability of concrete as determined by the "slump" test. For leaner mixtures and wetter consistencies the finer cements showed a somewhat greater "slump" than the coarser cements.

10. The normal consistency of cement is increased with fineness of grinding. About 0.1 per cent of water (in terms of the weight of the cement) must be added for each 1 per cent reduction in residue on the No. 200 sieve.

11. The time of setting of the cement is shortened with finer grinding. In some instances initial setting time with the Vicat needle was shortened to 5 to 10 minutes.

12. The unit weight of cement decreases with fineness. For the cements used in these tests the weight varied from 76 (residue of 2.4 per cent) to 108 lb. per cu. ft. (residue 43.3 per cent). For the usual range in fineness the weight is lowered about ¾ lb. per cu. ft. for each 1 per cent reduction in the residue on the No. 200 sieve.

13. In using 94 lb. per cu. ft. as a uniform basis for proportioning the cements in these tests, the actual volume of cement in a batch *of the same mix* varies about 35 per cent. If the mixtures had been proportioned in a manner that would have given a uniform *volume* of cement, the resulting concrete strength would not have been so favorable to the finer cements.

14. The fineness of cement has no appreciable effect on the yield or density of concrete.

15. Concrete of all mixes and consistencies showed expansion in damp sand or water storage and contraction in air.

16. The change in length of concrete specimens stored in air or water is independent of the fineness of the cement and the consistency of the concrete. The lean concretes are slightly less affected than the rich mixtures.

17. The type of aggregate has little or no influence on the relative effect of fineness of cement on the strength of concrete.

18. The tests included in this report show an intimate relation between the strength of the concrete and the water ratio of the mixture. The lower the water-ratio (so long as the concrete is plastic and the aggregate not too coarse) the higher the strength, and vice versa. This confirms the results of other concrete tests made in this Laboratory. Increasing the quantity of cement in a given mixture enables us to secure a concrete of equal workability with a lower water-ratio, hence a higher strength.

19. In ordinary concrete mixtures (say, 1:5 to 1:4, requiring 20 to 25 per cent cement, by volume) increasing the cement content by 1 per cent (to 20.2 per cent for a 1:5 mix) gives an increase in strength of about 1 per cent.

20. One per cent increase in cement is more effective in increasing the strength of concrete in lean than in rich mixtures.

21. One per cent increase in cement is somewhat more effective in increasing the early strength of concrete than at later periods.

22. The effect of increasing the quantity of cement is independent of the consistency of the concrete.

23. Tension tests of briquettes do not give a correct measure of the relative merits of different cements as determined by compression tests of mortar and concrete.

EFFECT OF FINENESS OF CEMENT

By Duff A. Abrams.

Introduction.

The recent revision of the Standard Specifications for Portland Cement focused attention on the function of the fineness of grinding of cement in producing concrete of high strength and other desirable properties. The effect of fineness of cement has been investigated by many experimenters during the past sixty years. The earliest experimental study which has come to the writer's attention is that made by John Grant, as a part of his investigation during the construction of the London Main Drainage Works. The results of these tests were published originally in the Proceedings of the Institution of Civil Engineers, 1865 and 1870. The report has since been reprinted in book form under the title of "Strength of Cement." A great many tests on the effect of fineness of cement have been carried out by German and French investigators. The principal investigations heretofore made in this country were carried out by the Bureau of Standards.

In spite of all of the experimental work which has been done on this subject, it was found by the committee engaged in the revision of the cement specifications that little or no definite information was available with reference to the effect of fineness of cement on the *strength of concrete*. Most of the published tests refer to briquettes or other small mortar specimens. In general, the published tests are inconclusive on account of the restricted scope of the investigations, or due to the narrow range in finenesses used.

Acknowledgment.

Acknowledgment is made to the cement manufacturers who furnished the cements; to the Chicago Gravel Co., for sand and pebble aggregate; to the Illinois Improvement and Ballast Co., Chicago, for crushed blast-furnace slag, and to the U. S. Shipping Board, Philadelphia, for burnt shale aggregate used in these tests.

Scope of Tests.

Investigations of the effect of fineness of cement have been under way at Lewis Institute for the past four years. Five independent series of tests have been completed. Another series now under way is not included in this report. The first series of tests (No. 20) was carried out

in cooperation with the Sub-Committee on Strength of Committee C-1 on Cement of the American Society for Testing Materials, and the results are here presented by permission of the committee. Subsequent studies were made as a part of the investigation of concrete and concrete materials being carried out through the cooperation of the Portland Cement Association and Lewis Institute.

The cements used were from seven commercial mills, representing the principal cement-producing districts east of the Mississippi River. The samples were ground at the mill to 4 to 7 degrees of fineness which gave residues ranging from 2 to 43 per cent on the standard No. 200 sieve. Fifty-one different samples of cement were used. In general, the aggregate consisted of sand and pebbles; in one series blast-furnace slag and a light-weight aggregate consisting of burnt shale were used.

These investigations include the following tests:

Concrete
- Compression tests of 6 by 12-in. cylinders.....6125

Cement and Mortar
- Compression tests of 2 by 4-in. cylinders.....4935
- Tension tests of briquettes.....4065

Miscellaneous tests of cement and aggregate..... 800
Chemical analysis of cement..... 100
"Slump" tests for consistency of concrete.....2300
Modulus of elasticity of concrete.....3200

Definite information has been secured on the effect of fineness of cement under the following conditions:

(*a*) Effect of fineness of cement on the strength of concrete (Residue 2 to 43 per cent on No. 200 sieve);
(*b*) Quality of concrete using different cements (51 samples from 7 different mills);
(*c*) Effect of the quantity of cement used (Mixes from 1:10 to neat cement);
(*d*) Effect of consistency of the concrete (Relative consistency 0.90 to 2.00);
(*e*) Effect of size and grading of the aggregate (No. 0–28 sand to 0–1½ in. aggregate);
(*f*) Variation in the type of aggregate (Sand and pebbles, blast furnace slag and burnt shale);
(*g*) Effect of age of concrete (7 days to 1 year);
(*h*) Elongation and contraction of concrete (Different mixes and consistencies for water and air storage up to 4 months);
(*i*) Effect of fineness of cement on workability of concrete.

The results of the modulus of elasticity tests are not included in this report.

OUTLINES OF TEST SERIES.

Skeleton outlines of the tests of each of the series (Tables 1 to 3) give the principal characteristics of the cements and indicate the variations in mix, consistency, size and grading of aggregate, etc. The series numbers furnish a convenient method of reference in identifying the tests.

TABLE 1—OUTLINES OF TESTS—SERIES 20, 31 AND 60.

Tension tests of briquettes and compression tests of 2 by 4-in. and 6 by 12-in. cylinders.
Mortar specimens mixed 5 in a batch, 1 for each age.
Concrete specimens proportioned and mixed in separate batches.
Mortar specimens stored in water; tested damp.
Concrete specimens stored in damp sand; tested damp.
Normal consistency mixtures.

Fineness of Cement Residue on No. 200 Sieve.	Form of Specimen.	Mix.	Aggregate.			Age at Test.	Specimens in a Set.	Number of Specimens.
			Kind.	Size.	F. M.			
SERIES 20.								
A B C D E 12.5 12.1 16.1 16.1 10.6 16.9 16.5 20.6 20.3 15.3 19.9 20.4 26.5 22.3 18.9	Briquettes 2 by 4-in. Cylinders.	Neat[1] 1:2 1:3 1:4	Standard sand Elgin sand	No. 20-30 0–No. 4	2.67 3.00	7 d. 28 d. 3 mo. 6 mo.	4	3900
22.9 23.0 33.3 25.6 23.7	6 by 12-in. Cylinders.	1:2:4 1:3:5	Elgin sand and pebbles	0–1¼ in.	5.60 5.43	1 yr.		600
SERIES 31.								
F G H 4.9 2.2 12.0 8.7 7.9 19.9 14.2 12.9 23.3	Briquettes 2 by 4-in. Cylinders.	Neat[1] 1:3	Standard sand Elgin sand	No. 20–30 0–No. 4	2.67 3.00	7 d.		2650
17.9 19.9 25.1 24.5 25.2 30.1 28.1 29.6 .... 33.4 34.0	6 by 12-in. Cylinders.	1:1½:3 1:1¾:3½ 1:2:4 1:2½:5 1:3:6	Elgin sand and pebbles	0–1¼ in.	5.53	28 d. 3 mo. 6 mo. 1 yr.	4	2375
SERIES 60								
F 4.9 8.7 14.2 17.9 24.5 28.1 33.4	2 by 4-in. Cylinders.	1:2.55	Elgin sand by volume.	0–No. 4 0–No. 4 0–No. 4 0–No. 4 0–No. 8 0–No. 4	4.44 4.06 3.63 3.17 3.00 2.53	7 d. 28 d. 3 mo. 6 mo. 1 yr.	5	1050

[1]Briquettes only

Series 20 was begun in August, 1915. Five different cements were used, each ground to 4 different degrees of fineness varying from about 10 to 33 per cent residue on the No. 200 sieve. Two concrete mixtures were used and three mortar mixtures. Tests were made at ages of 7 days to 1 year.

Series 31, an outgrowth of the tests in Series 20, was begun March, 1916. It was felt that a sufficient number of finenesses was not used in Series 20, consequently in Series 31 two cements were ground to 7 different degrees of fineness, and one to 5 degrees; the fineness varied from about 2 to 34 per cent residue. In this series greater emphasis was placed on the concrete than on the mortar tests. Five different concrete mixtures were used and two mortar mixtures. Tests were made for all conditions at ages of 7 days to 1 year.

Series 60 (October, 1916) was outlined for the purpose of determining the effect of fineness of cement on the strength of mortars made of sands of different grading. Six different gradings were made up using sand from Elgin, Ill., each graded to No. 4 sieve. Compression tests were made on 2 by 4-in. cylinders using Cement F from Series 31, ground to 7 different degrees of fineness.

TABLE 2—OUTLINE OF TESTS—SERIES 118.

Compression tests of 6 by 12-in. concrete cylinders. Hand-mixed concrete.
Concrete for each cylinder proportioned and mixed in a separate batch.
Plasticity determined by the "slump" method.
Five tests in a set made on different days.
Stored in damp sand; tested at 28 days.
Cement I-1, same as that used in concrete ship "Atlantus."
Cement I-2, standard mill product purchased from local contractor, Brunswick, Ga.
Cements K and L, different brands ground to 5 degrees of fineness.

Ref. No.	Cement. Fineness, Residue on No. 200 Sieve.[1]	Cement. Normal Consistency.	Mix by Volume.	Relative Consistency.	Aggregate. Kind.	Aggregate. Grading.	Number of Tests.
I-1....	8.9	23.5	1:1¾	0.90 1.00 1.05 1.10 1.15 1.20 1.25 1.50	Shale, slag, sand and celite (*Same aggregate* and proportions as in concrete ship "Atlantus.")	0–⅜ in.	48
I-2....	13.9	22.8					
K-1...	2.4	25.0	1:4	0.95 1.00 1.05 1.10 1.15 1.20 1.25 1.50 2.00	Elgin sand and pebbles.	0–¾ in.	225
K-2...	9.4	23.4					
K-3...	17.7	23.0					
K-4...	27.9	22.8					
K-5...	36.2	22.2					
K-1...	2.4	25.0	1:1¾	0.95 1.00 1.05 1.10 1.15 1.20 1.25 1.50 2.00	Crushed blast - furnace slag, sand and celite. (Grading of aggregate and mix, same as in concrete ship "Atlantus.")	0–⅜ in.	360
K-2...	9.4	23.4					
K-3...	17.7	23.0					
K-4...	27.9	22.8					
K-5...	36.2	22.2					
L-1...	7.1	23.4					
L-2...	16.3	22.9					
L-3...	28.9	21.8					
L-4...	32.3	21.4					
L-5...	43.3	20.0					

[1]Values for Cement K are the average of 15 to 18 tests; Cement L, 5 to 7 tests, and for Cement I, 3 tests In these tests 3 to 5 different standard sieves were used.

Series 118 (November, 1918) was carried out primarily for the purpose of studying the effect of fineness of cement using concretes of rich mixtures and different consistencies. Two of the cements were ground to 5 degrees of fineness. For the third cement (I) only 2 degrees of fineness were available. Cements I differed from the others in that they were not prepared from the same lot of clinker. Cement I-1 was used in the reinforced concrete ship "Atlantus" constructed at Brunswick, Ga. The samples were furnished by the U. S. Shipping Board for use in these tests. I-2 was the commercial product of the same brand, purchased from a contractor in Brunswick. In this series the aggregate was of small size, the purpose being to use the same mixture and aggregate of the size employed in reinforced concrete ship construction. The burnt shale aggregates were the same as that used in the ship "Atlantus." The coarse aggregate in this case consisted of burnt shale which, after crushing, was

graded in size up to about ⅜ in. Small quantities of "celite" * and fine sand were also used in the mixture. In another group in this series the mixtures and grading of aggregate were the same as those described above, except that blast-furnace slag was substituted for burnt shale. In the third group a 1:4 mix was used with sand and pebbles from Elgin, Ill. All tests were made at the age of 28 days.

TABLE 3—OUTLINE OF TESTS—SERIES 120.

Compression tests of 6 by 12-in. concrete cylinders. Hand-mixed concrete.
Concrete for each cylinder proportioned and mixed in a separate batch.
Cements ground at the mill to 5 different degrees of fineness.
Aggregate, sand and pebbles from the Elgin, Ill., pit of the Chicago Gravel Co.
Plasticity measured by the "slump" method.
Stored in damp sand; tested damp.
Cylinders in a set mixed on different days.

Ref. No.	Cement. Fineness, Residue on No. 200 Sieve.[1]	Cement. Normal Consistency.	Mix by Volume.	Size of Aggregate.	Relative Consistency.	Age at Test.	Cylinders in Set.	Total Cylinders.
K-1...	2.4	25.0	1:10	0–1½ in.	0.90	28 d.	6[a]	1080
K-2...	9.4	23.4	1:7		1.00			
K-3...	17.7	23.0	1:5		1.10			
K-4...	27.9	22.8	1:4		1.25			
K-5...	36.2	22.2	1:3		1.50			
			1:2		2.00			
K-1...	2.4	25.0	1:4	0–1½ in.	0.90	7 d.	5	450
K-2...	9.4	23.4			1.00			
K-3...	17.7	23.0			1.10	3 mo.		
K-4...	27.9	22.8			1.25	1 yr.		
K-5...	36.2	22.2			1.50			
					2.00			
K-1...	2.4	25.0	1:4	0–No. 28	1.10	7 d.	5	700
K-2...	9.4	23.4		0–No 14		28 d.		
K-3...	17.7	23.0		0–No. 8		3 mo.		
K-4...	27.9	22.8		0–No. 4		1 yr.		
K-5...	36.2	22.2		0–⅜ in.				
				0–¾ "				
				0–1½ "				
K-1...	2.4	25.0	1:4	0–No. 28	1.10	Elongation and Contraction tests only.	1	35
K-2...	9.4	23.4		0–No. 14				
K-3...	17.7	23.0		0–No. 8				
K-4...	27.9	22.8		0–No. 4				
K-5...	36.2	22.2		0–⅜ in.				
				0–¾ "				
				0–1½ "				
L-1...	7.1	23.4	1:10	0–1½ in.	0.90	28 d.	3	540
L-2...	16.3	22.9	1:7		1.00			
L-3...	28.9	21.8	1:5		1.10			
L-4...	32.3	21.4	1:4		1.25			
L-5...	43.3	20.0	1:3		1.50			
			1:2		2.00			

[1] Values for Cement K are the average of 15 to 18 tests; for Cement L, 5 to 7 tests. In these tests 3 to 5 different standard sieves were used.

[a] One round reserved for measurements of elongation and contraction.

Series 120 (begun December, 1918) was carried out with 2 cements, each ground at the mill to 5 finenesses varying from 2 to 43 per cent residue. The principal feature of the tests was a study of the effect of fineness for a wide range of mixtures, consistencies, size and grading of aggregates, and age of concrete. In two groups of tests measurements of elongation and contraction were made on 6 by 12-in. cylinders stored in damp sand, air and water.

*A siliceous material commonly known as kieselguhr, supposedly of diatomaceous origin.

TABLE 4—MISCELLANEOUS TESTS OF CEMENTS.

Series	Cement Ref. No.	Fineness, Residue on Sieve No. 100	Fineness, Residue on Sieve No. 200	Per Cent Flour.[1]	Weight, lb. per cu. ft.	Normal Consistency, per cent by Weight.	Time of Setting. Vicat Needle. Initial. h m	Vicat Needle. Final. h m	Gillmore Needle. Initial. h m	Gillmore Needle. Final. h m	Soundness Test (Over boiling water).
20	A-1	1.7	12.5	35.5	.....	23.0	1–15	5–00	3–00	6–00	O K
20	A-2	2.8	16.9	32.6	.....	23.0	2–15	6–00	3–00	6–30	"
20	A-3	3.6	19.9	30.3	.....	22.5	2–30	7–00	4–00	7–30	"
20	A-4	4.3	22.9	29.3	.....	22.0	2–15	7–30	3–45	7–30	"
20	B-1	1.5	12.1	37.4	.....	23.0	1–15	4–00	2–50	4–45	"
20	B-2	2.2	16.5	33.8	.....	23.0	1–15	4–00	3–00	5–00	"
20	B-3	3.5	20.4	32.3	.....	23.0	1–45	4–45	3–15	6–00	"
20	B-4	4.5	23.0	30.4	.....	23.0	1–45	5–00	3–15	6–00	"
20	C-1	2.8	16.1	30.5	.....	21.0	2–15	6–00	3–00	6–00	"
20	C-2	4.7	20.6	31.1	.....	20.0	1–45	5–00	2–50	5–00	"
20	C-3	9.3	26.5	29.1	.....	19.5	1–50	5–00	3–00	5–00	"
20	C-4	13.3	33.3	.....	.....	19.0	2–35	6–00	3–00	6–00	"
20	D-1	1.8	16.1	33.9	.....	22.5	4–30	8–45	5–30	8–45	"
20	D-2	2.4	20.3	29.1	.....	22.0	4–45	8–45	5–45	8–45	"
20	D-3	4.1	22.3	30.9	.....	21.5	4–00	8–45	5–00	8–45	"
20	D-4	5.0	25.6	27.8	.....	21.0	4–00	8–45	5–00	8–45	"
20	E-1	1.2	10.6	37.3	.....	24.5	3–30	6–30	4–45	8–45	"
20	E-2	1.8	15.3	33.8	.....	24.0	3–00	6–30	4–45	8–45	"
20	E-3	2.9	18.9	31.3	.....	23.5	3–00	6–40	4–30	8–30	"
20	E-4	4.9	23.7	30.1	.....	23.0	3–00	6–30	4–15	8–20	"
31	F-1	1.4	4.9	.....	.....	29.0	0– 5	3–45	2–30	6–30	"
31	F-2	1.3	8.7	.....	.....	28.0	0– 7	4–15	2–45	6–30	"
31	F-3	1.7	14.2	.....	.....	27.0	0–20	6–20	3–30	7–15	"
31	F-4	2.7	17.9	.....	.....	26.0	0–17	7–00	4–30	8–00	"
31	F-5	5.2	24.5	.....	.....	25.0	0–15	6–30	4–30	8–00	"
31	F-6	7.5	28.1	.....	.....	24.5	0–15	6–30	4–15	8–00	"
31	F-7	11.6	33.4	.....	.....	24.0	2–00	7–15	4–30	7–45	"
31	G-1	0.8	2.2	.....	.....	29.0	0–25	3–45	2–15	4–30	"
31	G-2	0.9	7.9	.....	.....	26.0	2–45	4–00	4–00	5–30	"
31	G-3	1.2	12.9	.....	.....	25.0	4–00	7–15	4–30	7–45	"
31	G-4	2.7	19.9	.....	.....	25.0	0–50	9–00	6–00	9–45	"
31	G-5	5.8	25.2	.....	.....	24.5	4–30	8–45	6–00	9–00	"
31	G-6	6.8	29.6	.....	.....	24.5	5–45	9–30	6–30	9–30	"
31	G-7	11.0	34.0	.....	.....	24.0	4–15	9–45	5–20	9–45	"
31	H-1	1.9	12.0	.....	.....	23.0	1–40	5–00	3–00	6–15	"
31	H-2	3.3	19.9	.....	.....	23.0	2–10	5–45	3–45	7–15	"
31	H-3	4.7	23.3	.....	.....	21.5	1–45	5–45	3–10	6–15	"
31	H-4	5.9	25.1	.....	.....	22.0	2–45	6–15	3–45	7–00	"
31	H-5	10.9	30.1	.....	.....	22.0	3–10	7–00	4–15	7–30	"
60	F-1	1.4	4.9	.....	.....	26.0	1–25	4–35	3–20	5–25	"
60	F-2	1.3	8.7	.....	.....	26.0	1–20	5–20	2–55	5–45	"
60	F-3	1.7	14.2	.....	.....	24.5	2–20	6–15	4–00	7–40	"
60	F-4	2.7	17.9	.....	.....	24.0	1–10	8–15	3–40	10–30	"
60	F-5	5.2	24.5	.....	.....	23.0	2–40	7–05	4–05	8–20	"
60	F-6	7.5	28.1	.....	.....	22.0	1–10	8–50	3–40	10–30	"
60	F-7	11.6	33.4	.....	.....	22.0	2–55	6–55	4–35	8–25	"
118 and 120	I-1	.....	8.9	.....	90	23.5	5–45	11–20	6–25	12–00	"
118 and 120	I-2	.....	13.9	.....	95	22.8	6–20	12–00	7–40	13–05	"
118 and 120	K-1	.....	2.4	.....	76	25.1	0–30	4–45	4–30	6–45	"
118 and 120	K-2	.....	9.4	.....	84	23.4	3–50	6–50	5–20	11–05	"
118 and 120	K-3	.....	17.7	.....	91	23.0	5–00	11–45	5–55	13–15	"
118 and 120	K-4	.....	27.9	.....	100	22.8	6–15	12–25	7–25	13–30	"
118 and 120	K-5	.....	36.2	.....	104	22.2	5–55	13–15	6–40	14–10	"
118 and 120	L-1	.....	7.1	.....	82	23.4	4–25	12–20	6–45	14–10	"
118 and 120	L-2	.....	16.3	.....	91	22.9	4–50	12–45	7–00	13–50	"
118 and 120	L-3	.....	28.9	.....	99	21.8	5–55	13–10	6–45	14–20	"
118 and 120	L-4	.....	32.3	.....	104	21.4	5–20	14–20	6–55	15–00	"
118 and 120	L-5	.....	43.3	.....	108	20.0	6–30	14–45	7–10	15–10	"

[1] Tests made by the Bureau of Standards in accordance with the methods described in Technologic Paper No. 48 "An Air Analyzer for Determining the Fineness of Cement." See Table 5 for results of air analyzer tests made in this Laboratory.

MATERIALS.

The cements used represented the product of 7 commercial mills. The samples of a given cement (except Cements I) were ground from the same clinker to the different degrees of fineness shown in the tables. The finenesses used gave an extreme variation of 2 to 43 per cent residue on the No. 200 sieve. Each lot of cement is referred to by a letter, samples of different fineness being designated by an attached figure. The figure 1 following the letter designates the finest cement; the other finenesses follow in order. Miscellaneous tests of the cements are given in Tables 4 and 5. Table 6 gives chemical analysis of the cements. Strength tests of the cements are included in the tables accompanying each series.

TABLE 5—MECHANICAL ANALYSES OF CEMENTS—SERIES 118–120.

Analysis of material finer than No. 200 sieve made in air analyzer (see Fig. 3).

Cement Lot No.	Amount Coarser than Each Size, per cent by Weight.						
	Air Analyzer No.				Sieve No.		
	D (0.00035)[1]	C (0.00075)	B (0.00130)	A (0.00181)	200 (0.0038)	100 (0.0066)	48 (0.0137)
K-1	73.7	44.0	22.4	14.0	2.4	0.6	0
K-2	74.7	58.9	38.5	28.9	9.4	0.5	0
K-3	79.3	65.5	46.5	38.4	17.7	2.0	0
K-4	82.5	70.8	55.0	47.6	27.9	7.6	0.4
K-5	86.3	75.6	60.7	54.8	36.2	15.2	1.5
L-1	68.7	51.1	34.2	25.5	7.1	0	0
L-2	75.5	60.5	42.8	34.2	16.3	0.9	0
L-3	84.2	72.1	56.0	49.8	28.9	12.1	3.2
L-4	85.2	74.3	58.7	52.0	32.3	13.8	4.4
L-5	86.8	76.5	63.3	58.2	43.3	26.1	12.4

[1]Separation size in inches. The separation size is the diameter of the sphere having a volume equal to the volume of the last particles passing the sieve or discharged by the air analyzer. Separation size $= \sqrt[3]{L \times M \times S}$, where L, M and S are the three dimensions of the particles. These dimensions were determined by microscopic measurements on a large number of particles. In making these measurements we followed the methods developed by the Bureau of Standards as described in their Technologic Paper No. 48. Due to the elongated shape of the last particles passing the sieves the separation size is larger than the clear opening of sieve; for example, the clear opening of the standard No. 200 sieve is 0.0029 in.

Sand and pebbles from a pit of the Chicago Gravel Co., near Elgin, Ill., were used as aggregate in most of the tests. In Series 118 three different aggregates were used; burnt shale manufactured for the U. S. Shipping Board, mixed with small quantities of celite and fine sand from Brunswick, Ga.; aggregates consisting of Elgin sand and crushed blast-furnace slag up to ⅜ in., and Elgin sand and pebbles. General information concerning aggregates will be found in Table 7. In cases where different sizes of Elgin sand were used, the material was obtained by screening out the coarser sizes from the commercial product. The pebbles were screened to 3 sizes (No. 4 to ⅜ in.; ⅜ in. to ¾ in. and ¾ to 1½ in.) and recombined for each batch to the sieve analysis shown.

TABLE 6—CHEMICAL ANALYSIS OF CEMENTS.

Cement Ref. No.	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	CO_2	Insoluble Residue.	Loss on Ignition.
SERIES 20.									
A-1	21.12	7.20	1.88	63.41	2.03	1.53	0.75	0.30	2.34
A-2	21.32	7.34	1.85	63.45	1.93	1.45	0.38	0.25	2.15
A-3	21.32	7.30	1.85	63.73	1.95	1.33	0.30	0.18	1.83
A-4	21.38	7.31	1.85	63.30	1.92	1.47	0.31	0.18	2.09
B-1	19.58	7.31	2.75	63.38	1.54	1.43	0.95	0.20	3.92
B-2	19.72	7.33	2.75	63.80	1.67	1.37	0.73	0.20	3.24
B-3	19.94	7.29	2.85	63.24	1.68	1.35	0.98	0.20	3.52
B-4	19.74	7.51	2.70	64.08	1.59	1.30	0.73	0.17	2.99
C-1	22.04	5.41	2.10	63.10	2.88	1.85	0.71	0.15	2.10
C-2	22.30	5.35	2.03	63.10	2.99	1.55	0.58	0.30	2.03
C-3	22.08	5.52	2.20	63.03	2.92	1.65	0.60	0.30	2.20
C-4	22.04	5.85	2.01	62.96	2.95	1.64	0.69	0.22	2.01
D-1	21.60	6.76	2.80	62.45	1.90	1.26	0.98	0.19	2.43
D-2	21.64	6.81	2.95	62.72	1.76	1.82	0.37	0.25	1.90
D-3	21.76	7.04	2.90	62.52	1.79	1.63	0.40	0.19	1.96
D-4	21.94	6.44	2.80	63.01	1.95	1.32	0.34	0.25	1.55
E-1	19.76	8.15	3.75	63.12	1.02	2.03	0.42	0.45	1.48
E-2	19.76	8.03	3.75	63.33	1.04	1.96	0.32	0.41	1.55
E-3	19.54	7.97	3.75	63.82	1.09	1.89	0.45	0.37	1.60
E-4	19.56	8.11	3.75	63.40	1.09	2.01	0.42	0.32	1.46
SERIES 31 AND 60.									
F-1	19.24	7.78	3.16	63.62	1.20	1.72	....	....	2.65
F-2	19.10	7.84	3.08	63.71	1.24	1.67	....	....	2.53
F-3	19.10	7.78	3.12	63.76	1.20	1.70	....	....	2.50
F-4	19.10	7.94	3.04	63.76	1.23	1.93	....	....	2.20
F-5	19.10	7.78	3.12	63.97	1.19	1.85	....	....	2.43
F-6	19.08	7.78	3.12	63.97	1.26	1.70	....	....	2.45
F-7	19.14	7.61	3.04	64.09	1.49	1.75	....	....	2.27
G-1	20.36	7.15	1.85	63.45	2.03	1.51	....	....	3.02
G-2	21.14	7.36	1.80	64.16	2.08	1.29	....	....	1.60
G-3	20.98	7.40	1.80	64.01	1.93	1.50	....	....	1.65
G-4	20.52	7.30	1.90	64.01	2.03	1.56	....	....	2.05
G-5	20.94	7.25	1.85	64.08	1.97	1.37	....	....	1.86
G-6	20.94	7.39	1.75	64.16	1.98	1.56	....	....	1.70
G-7	21.10	7.35	1.75	64.08	1.95	1.46	....	....	1.75
H-1	22.13	6.65	2.70	61.56	2.42	1.93	....	....	2.39
H-2	20.95	6.27	2.60	60.35	2.37	3.77	....	....	3.15
H-3	21.67	6.79	2.70	61.27	2.50	2.20	....	....	2.50
H-4	21.71	6.83	2.70	61.42	2.44	2.40	....	....	2.55
H-5	21.81	6.77	2.70	61.13	2.51	2.63	....	....	2.62
SERIES 118 AND 120.									
I-1	21.05	10.97		62.56	1.20	1.42	1.04	0.66	2.84
I-2	22.23	10.33		62.64	0.85	1.43	1.40	0.61	3.30
K-1	19.95	10.11		62.07	2.21	1.93	0.82	0.80	3.14
K-2	19.71	10.52		63.37	2.40	1.99	0.71	0.23	1.92
K-3	19.80	11.35		62.45	2.31	2.03	1.15	0.35	2.34
K-4	20.78	11.41		61.83	2.28	2.07	3.51	0.48	1.92
K-5	20.03	8.19		64.92	1.86	2.09	0.42	0.84	2.14
L-1	22.24	9.04		62.61	2.05	1.90	0.67	0.94	2.14
L-2	21.63	9.31		62.95	1.58	1.90	0.83	0.10	2.41
L-3	22.45	8.92		63.16	2.00	1.93	0.75	0.50	2.05
L-4	22.27	9.34		63.16	1.70	1.90	0.89	0.80	2.29
L-5	22.11	9.46		62.26	2.06	1.95	0.96	0.53	3.00

NOTE.—Analysis of Cements B were made after 6 months storage in laboratory; CO_2 and loss on ignition are high on this account.

TABLE 7—MISCELLANEOUS TESTS OF AGGREGATES.

Material.	Size.	Weight, lb. per cu. ft.	Density.	Sieve Analysis. (Per cent Coarser than Each Sieve.) 100	48*	28*	14*	8	4	⅜ in.	¾ in.	1½ in.	Fineness Modulus.[1]
SERIES 20.													
Elgin sand	0–No. 4	108	0.646	98	90	68	47	24	0	..	..	..	3.27
Elgin pebbles	No. 4–1¼ in.	102	0.612	100	100	100	100	100	98	70	7	0	6.75
Elgin sand and pebbles (1:2:4 mix)	0–1¼ "	...	...	99	97	90	82	75	65	47	5	0	5.60
Elgin sand and pebbles (1:3:5 mix)	0–1¼ "	...	...	99	96	88	80	72	61	43	4	0	5.43
SERIES 31.													
Elgin sand	0–No. 4	106	0.636	99	90	61	35	16	0	..	..	..	3.01
Elgin pebbles	No. 4–1¼ in.	104	0.623	100	100	100	100	100	100	60	20	0	6.80
Elgin sand and pebbles	0–1¼ "	...	...	99	97	87	78	72	67	40	13	0	5.53
SERIES 60.													
Elgin sand N-14	0–No. 4	109	0.652	100	98	95	86	65	0	..	..	..	4.44
" " N-10	0–No. 4	112	0.670	99	94	88	75	50	0	..	..	..	4.06
" " N-7	0–No. 4	116	0.694	99	86	77	63	38	0	..	..	..	3.63
" " N-5	0–No. 4	119	0.713	97	75	65	50	30	0	..	..	..	3.17
" " N-S	0–No. 8	107	0.640	100	100	67	33	0	..	..	..	..	3.00
" " N-3	0–No. 4	116	0.698	96	57	47	35	18	0	..	..	..	2.53
SERIES 118.													
Brunswick sand	0–No. 14*	96	0.577	99	79	11	0	..	..	..	..	..	1.89
Burnt shale slag	0–⅜ in.	77	0.610	79	70	58	43	22	1	0	..	..	2.73
Burnt shale slag	No. 8–¾ "	53	0.522	100	100	100	100	100	85	11	0	..	5.96
Celite	.....	12	0.100	..	..	..	..	..	..	..	..	..	....
Mix of sand and shale slag[2]	0–¾ in.	73	0.618	92	86	74	67	59	38	5	0	..	4.70
Fine Elgin sand	0–No. 14*	109	0.655	89	50	13	5	1	0	..	..	..	1.58
Elgin sand	0–No. 4	115	0.688	99	93	58	37	20	2	0	..	..	3.10
Elgin pebbles	No. 4–¾ in.	105	0.629	100	100	100	100	100	100	67	0	..	6.67
Elgin pebbles	No. 4–⅜ "	105	0.629	100	100	100	100	100	100	0	..	..	6.00
Slag	0–No 4	100	0.666	94	89	80	63	40	0	..	..	..	3.66
Slag	No. 4–⅜ in.	90	0.599	100	100	100	100	100	100	0	..	..	6.00
Mix of sand and shale slag[2]	0–⅜ "	108	0.721	96	92	85	78	67	51	0	..	..	4.70
Elgin sand and pebbles	0–⅜ "	121	0.725	98	95	72	57	45	33	0	..	..	4.00
Elgin sand and pebbles	0–¾ "	127	0.762	99	97	80	71	63	54	36	0	..	5.00
SERIES 120.													
Elgin sand	0–No. 28*	105	0.629	90	50	0	..	..	..	..	..	..	1.40
" "	0–No. 14*	107	0.641	96	87	31	0	..	..	..	..	..	2.14
" "	0–No. 8	109	0.653	99	89	45	17	0	..	..	..	..	2.50
" "	0–No. 4	115	0.688	99	91	59	36	20	0	..	..	..	3.05
" " and pebbles....	0–⅜ in.	119	0.712	99	94	72	56	46	32	0	..	..	4.00
" " " "	0–¾ "	126	0.754	99	96	81	71	63	54	36	0	..	5.00
" " " "	0—1½ in.	128	0.767	99	98	87	81	75	68	50	17	0	5.75

*(Note added to Revised Edition, November, 1922.) The No. 48, 28, and 14-mesh sieves give the same separation as the No. 50, 30, and 16 now used in the "Tentative Method of Test for Sieve Analysis of Aggregates for Concrete" of the American Society for Testing Materials. The No. 50, 30 and 16 sieves are now used in all our tests.

[1] The sum of percentages in the Sieve Analysis, divided by 100.

[2] Made up of 0.15 volumes of fine sand, 0.65 volumes of fine slag and 1.2 volumes of medium slag.

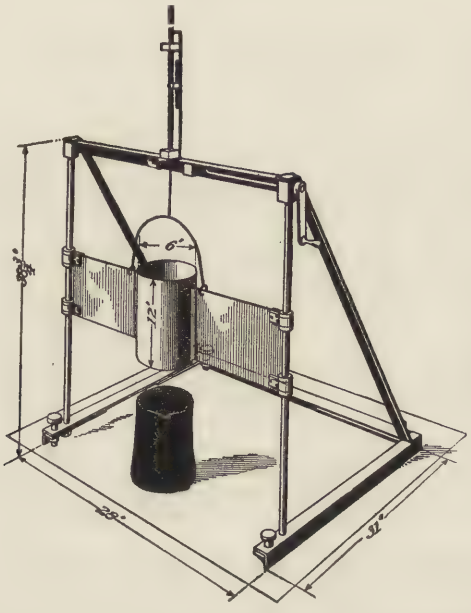


FIG. 1—APPARATUS USED IN "SLUMP" TEST OF WORKABILITY OF CONCRETE.

(Note added to Revised Edition, November, 1922.) Present practice in making the slump test for consistency or workability of concrete requires the use of a 4 by 8 by 12-in. truncated cone. For concrete of a given consistency the cone gives slumps about 2/3 that of the cylinder. The truncated cone is specified in the Progress Report of the Joint Committee on Standard Specifications for Concrete and Reinforced Concrete and is used in the Tentative Specifications for Workability of Concrete for Concrete Pavements of the American Society for Testing Materials.

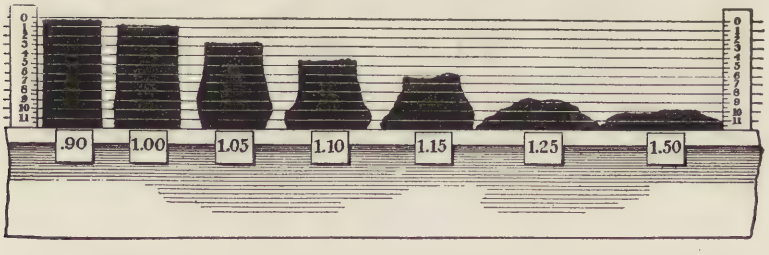


FIG. 2—SKETCH SHOWING APPEARANCE OF CONCRETE AFTER "SLUMP" TESTS.

The slump is measured on the vertical scale of inches. The sketch was made from a photograph of the concrete specimens after slump tests of 6 by 12-in. cylinders, using a 1:2½ mix, with sand and pebble aggregate graded to ¾ in. The figures under the specimens refer to the relative consistency of the concrete.

The "fineness modulus" of an aggregate is used as a measure of its size and grading. It is the sum of the percentages in the sieve analyss divided by 100. The sieve analysis is expressed in terms of weight or separate volumes coarser than each sieve. The sizes of sieves and fine-

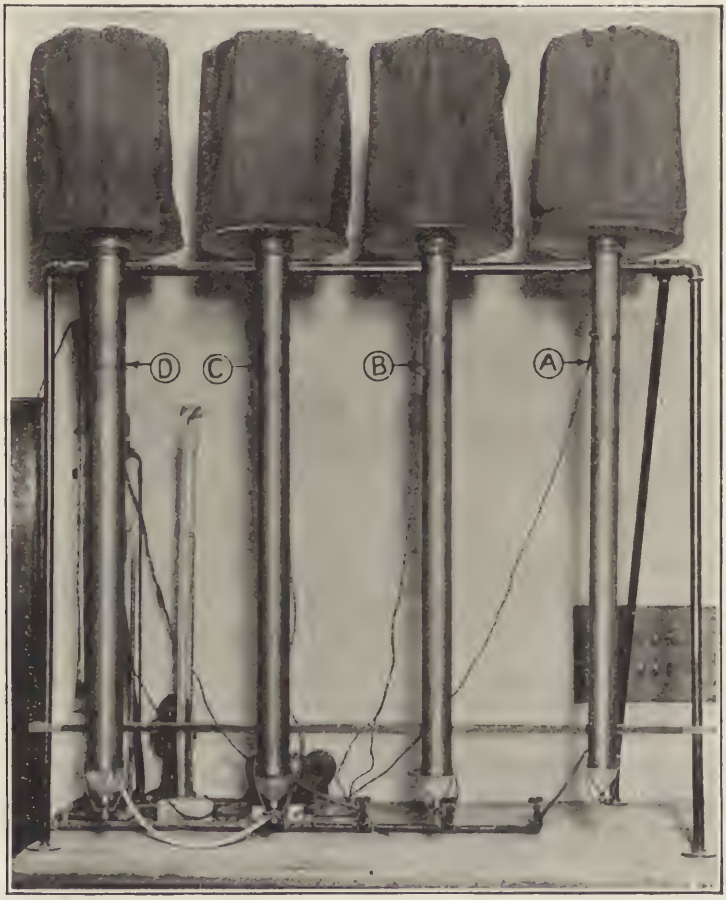


FIG. 3—AIR ANALYZER FOR MECHANICAL ANALYSIS OF CEMENT.
For details of tests see Table 5.

ness modulus of the aggregates used in these tests are shown in Table 7. Low values of fineness modulus (abbreviated to F. M. in the tables) correspond to small sizes and high values to the coarse sizes of aggregate.*

* For further details on fineness modulus of aggregates see the writer's report on "Design of Concrete Mixtures," *Bulletin 1*, Structural Materials Research Laboratory.

TEST PIECES.

The kind and numbers of test pieces used in each series are indicated in the outlines of the series, Tables 1 to 3. Specimens for compression tests of concrete consisted of 6 by 12-in. cylinders. Over 6100 specimens of this kind were tested. The concrete for each cylinder was proportioned separately and mixed by hand with a bricklayer's trowel in a shallow metal pan. Each batch consisted of about ⅛ cu. ft. of concrete. The forms consisted of 12-in. lengths of cold-drawn steel tubing split along one element. Each form stood on a machined cast-iron base plate. The specimens were molded by hand by placing the fresh concrete in the form in 4-in. layers and puddling with about 25 strokes of a ⅝-in. round steel bar

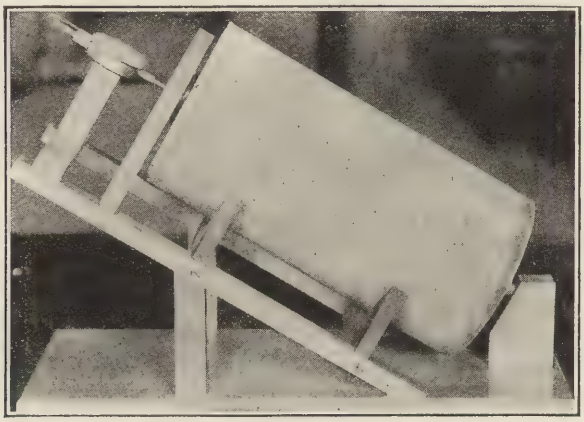


FIG. 4—APPARATUS FOR MEASURING ELONGATION AND CONTRACTION OF 6 BY 12-IN. CYLINDERS.

pointed at the lower end. A smooth top was formed by means of a neat cement cap placed on the cylinder from 2 to 4 hours after molding. The cement paste for capping was mixed at the same time, or prior to the mixing of the concrete. About 24 hours after molding, the metal form was removed and the specimen weighed, marked and stored in damp sand until the date of test.

The mixtures in Series 20 and 31 are expressed in terms of the volume of cement, fine aggregate and coarse aggregate—for instance 1:2:4—indicating a mixture in the proportions of 1 sack of cement (1 cu. ft. = 94 lb.), 2 cu. ft. of sand and 4 cu. ft. of coarse aggregate. The actual quantities for a batch were determined by weight, on the basis of the unit weights of the materials. In Series 118 and 120 the mixtures are expressed as one volume of cement to a given number of volumes of aggregate, regardless of the size and grading of the latter. A 1:5 mix ex-

TABLE 8—TENSION TESTS OF BRIQUETTES—SERIES 20.

Specimens stored in water; tested wet.
Each value is the average of 4 tests made on different days.

Cement.		Tensile Strength, lb. per sq. in.																			
		Neat.						1:2 Standard Sand.					1:3 Standard Sand.					1:4 Standard Sand.				
Ref. No.	Fineness, Residue on No. 200 Sieve.	1 d.	7 d.	28 d.	3 mo.	6 mo.	1 yr.	7 d.	28 d.	3 mo.	6 mo.	1 yr.	7 d.	28 d.	3 mo.	6 mo.	1 yr.	7 d.	28 d.	3 mo.	6 mo.	1 yr.
A-1	12.5	317	588	694	713	651	660	392	516	490	498	538	291	383	451	441	453	202	320	350	340	310
A-2	16.9	291	651	665	704	661	705	376	529	624	571	523	240	354	419	441	404	243	338	366	370	346
A-3	19.9	296	576	771	706	718	625	380	506	574	492	535	242	401	375	406	394	158	271	309	342	300
A-4	22.9	275	614	655	783	721	718	339	519	553	522	538	252	360	423	431	384	160	266	329	322	283
B-1	12.1	238	550	719	719	678	635	415	478	511	499	503	289	373	361	378	350	223	341	294	312	296
B-2	16.5	273	644	684	723	692	655	409	520	499	515	498	300	370	341	382	351	215	296	289	304	284
B-3	20.4	293	604	765	658	692	648	384	472	483	492	478	244	379	341	361	323	189	288	281	314	265
B-4	23.0	285	636	669	685	704	668	379	455	456	500	494	270	358	350	369	325	208	266	273	318	263
C-1	16.1	356	699	896	828	776	735	451	621	633	649	518	305	441	479	463	418	260	376	406	394	339
C-2	20.6	408	711	754	778	859	738	460	621	628	570	555	342	465	501	435	403	261	354	409	380	353
C-3	26.5	438	733	830	799	869	945	434	601	634	596	560	288	423	470	425	396	231	306	388	345	301
C-4	33.3	353	719	870	936	919	840	391	519	615	588	533	238	391	439	426	396	190	311	366	354	293
D-1	16.1	340	721	685	733	668	648	400	520	576	598	569	259	385	434	448	405	222	360	348	380	316
D-2	20.3	372	638	766	739	718	653	431	559	623	576	538	314	420	474	444	406	218	338	371	378	361
D-3	22.3	404	649	730	708	670	740	388	554	608	578	511	280	413	446	478	385	215	301	384	369	300
D-4	25.6	371	600	759	734	759	723	371	506	580	544	476	268	373	430	404	334	204	290	349	350	299
E-1	10.6	341	639	683	640	568	550	465	510	587	556	620	358	388	440	438	475	305	300	414	423	325
E-2	15.3	349	620	714	654	618	645	480	571	592	570	564	355	405	452	474	479	255	271	370	380	341
E-3	18.9	370	731	748	675	618	680	464	515	579	544	518	356	351	433	466	423	284	311	364	351	308
E-4	23.7	349	626	733	740	667	663	373	510	560	569	529	313	366	421	454	385	231	304	350	369	349
Average		336	647	740	733	711	694	409	530	570	551	530	290	390	424	428	394	224	310	351	355	312

(Continued on page 17)

TABLE 8—*Continued.*

Cement.		Tensile Strength, lb. per sq. in.																			
		Neat.						1:2 Elgin Sand.					1:3 Elgin Sand.					1:4 Elgin Sand.				
Ref. No.	Fineness, Residue on No. 200 Sieve.	1 d.	7 d.	28 d.	3 mo.	6 mo.	1 yr.	7 d.	28 d.	3 mo.	6 mo.	1 yr.	7 d.	28 d.	3 mo.	6 mo.	1 yr.	7 d.	28 d.	3 mo.	6 mo.	1 yr.
A-1	12.5	.....	.....	Not	Made	.....	.....	478	539	698	669	706	396	529	600	575	640	336	471	513	501	564
A-2	16.9	.....	.....	.....	.....	.....	.....	421	600	644	605	741	334	518	582	579	614	306	414	506	509	514
A-3	19.9	.....	.....	.....	.....	.....	.....	429	546	636	638	701	335	490	501	596	596	245	391	456	508	531
A-4	22.9	.....	.....	.....	.....	.....	.....	423	602	591	612	681	324	478	588	566	585	262	385	480	442	485
B-1	12.1	.....	.....	.....	.....	.....	.....	450	551	565	529	659	391	484	515	568	593	318	429	441	465	516
B-2	16.5	.....	.....	.....	.....	.....	.....	449	504	601	638	649	410	514	524	560	611	301	400	493	464	504
B-3	20.4	.....	.....	.....	.....	.....	.....	404	454	549	584	585	373	426	526	532	571	260	379	455	465	491
B-4	23.0	.....	.....	.....	.....	.....	.....	410	540	509	578	656	323	459	533	482	574	296	359	444	424	509
C-1	16.1	.....	.....	.....	.....	.....	.....	500	676	820	695	788	474	534	660	656	730	350	464	558	571	634
C-2	20.6	.....	.....	.....	.....	.....	.....	521	660	734	736	800	454	558	648	626	720	328	459	549	535	570
C-3	26.5	.....	.....	.....	.....	.....	.....	494	686	700	719	659	421	498	608	593	623	293	409	493	491	536
C-4	33.3	.....	.....	.....	.....	.....	.....	435	636	660	658	681	309	440	544	576	639	218	339	484	474	539
D-1	16.1	.....	.....	.....	.....	.....	.....	468	591	660	634	656	406	533	564	636	568	303	405	454	489	534
D-2	20.3	.....	.....	.....	.....	.....	.....	502	576	729	625	694	390	503	619	616	650	333	391	484	519	560
D-3	22.3	.....	.....	.....	.....	.....	.....	474	581	654	650	676	374	466	591	580	664	304	426	510	480	541
D-4	25.6	.....	.....	.....	.....	.....	.....	440	523	656	618	664	351	474	589	545	538	282	370	460	489	490
E-1	10.6	.....	.....	.....	.....	.....	.....	559	549	711	673	788	493	513	639	654	665	374	438	544	545	540
E-2	15.3	.....	.....	.....	.....	.....	.....	560	519	674	743	686	441	485	577	615	679	359	391	529	571	550
E-3	18.9	.....	.....	.....	.....	.....	.....	520	598	675	658	701	443	513	600	548	651	353	419	494	504	549
E-4	23.7	.....	.....	.....	.....	.....	.....	555	578	621	681	730	378	506	539	606	625	291	345	494	494	568
Average	.....	.....	.....	.....	.....	.....	.....	475	575	654	647	695	391	496	577	585	627	306	404	492	497	536

TABLE 9—COMPRESSION TESTS OF 2 BY 4-IN. CYLINDERS—SERIES 20.

Specimens stored in water; tested wet.
Each value is the average of 4 tests made on different days.

Cement.		Compressive Strength, lb. per sq. in.														
		1:2 Standard Sand.					1:3 Standard Sand.					1:4 Standard Sand.				
Ref. No.	Fineness. Residue on No. 200 Sieve.	7 d.	28 d.	3 mo.	6 mo.	1 yr.	7 d.	28 d.	3 mo.	6 mo.	1 yr.	7 d.	28 d.	3 mo.	6 mo.	1 yr.
A-1	12.5	2940	5070	6620	6790	6960	1600	3200	4060	4140	4180	1030	1680	2330	2400	2710
A-2	16.9	2370	4690	6050	5640	6570	1310	2950	3460	3820	4230	860	1550	2010	2200	2250
A-3	19.9	2290	4720	6180	5740	6870	1240	2650	3310	3380	4040	890	1410	2030	1950	1970
A-4	22.9	2250	4500	6080	6270	7290	1230	2610	3160	3640	3690	710	1290	1570	1910	2180
B-1	12.1	2880	4980	5780	6080	6760	1820	3030	3800	3600	4280	1000	1950	2310	2040	2250
B-2	16.5	3220	5360	6560	6600	6350	1870	3240	3720	4110	3950	1108	1860	2300	2140	2190
B-3	20.4	2390	4500	5750	5810	5860	1440	2740	3370	3400	3560	870	1720	1790	1820	2110
B-4	23.0	2650	4610	5670	5800	6330	1440	2540	3270	2990	3530	940	1520	2130	1640	1950
C-1	16.1	3980	7060	8530	9440	9600	2060	3700	5130	5360	5640	1100	1870	2620	2790	2910
C-2	20.6	3490	6240	8510	8640	9030	1700	3330	4360	5030	5220	1080	1750	2340	2560	2780
C-3	26.5	3230	5480	7250	8020	8030	1590	2610	3690	3970	4160	810	1810	2100	2360	2420
C-4	33.3	2660	4850	6760	6960	7310	1420	2230	3500	3710	3500	670	1210	1990	2210	1750
D-1	16.1	3130	5040	6170	6730	7410	1600	2760	3620	4380	4270	810	1820	2020	2640	2650
D-2	20.3	3140	5640	6910	7260	7280	1650	2920	3940	4220	4520	1180	1660	2450	2500	2850
D-3	22.3	2870	4950	6280	7150	7380	1670	2910	3920	3840	4300	960	1940	2380	2600	2630
D-4	25.6	2850	5160	6690	5990	7370	1550	2830	3940	3700	4150	640	1700	1800	2200	2190
E-1	10.6	4110	5970	6990	8160	7920	2450	4200	4630	5370	5370	1490	2430	2920	2990	2810
E-2	15.3	3940	6020	7030	7110	8110	2350	3510	4460	4980	5060	1350	1790	2660	2970	3240
E-3	18.9	4080	6430	7270	7850	8190	2440	3470	4660	4200	4550	1460	2170	3050	2840	2640
E-4	23.7	3230	5540	6950	6800	7350	1930	2620	3900	4180	4760	1390	2170	2690	3060	3230
Average		3090	5340	6700	6940	7400	1720	3000	3900	4100	4350	1020	1770	2270	2390	2940

(Continued on page 19)

TABLE 9—*Continued.*

Cement.		Compressive Strength, lb. per sq. in.														
Ref. No.	Fineness, Residue on No. 200 Sieve.	1:2 Elgin Sand.					1:3 Elgin Sand.					1:4 Elgin Sand.				
		7 d.	28 d.	3 mo.	6 mo.	1 yr.	7 d.	28 d.	3 mo.	6 mo.	1 yr.	7 d.	28 d.	3 mo.	6 mo.	1 yr.
A-1	12.5	3770	5860	6980	8000	7800	2840	4910	6260	6430	6980	2090	3620	5000	5040	5280
A-2	16.9	3070	5610	7090	7250	7210	2500	4540	5810	6080	6850	1760	3460	4230	4560	4790
A-3	19.9	3000	5430	6950	6490	7590	2260	4470	5600	5790	6590	1500	2930	4100	4100	4450
A-4	22.9	2890	4990	7080	6840	7640	2270	4050	5160	5800	6360	1320	2510	3620	3910	4350
B-1	12.1	3480	5580	6680	7060	7580	3000	4770	5590	5590	6900	2260	3540	4660	4590	5090
B-2	16.5	3680	5930	7320	7610	7830	2960	4780	5720	6060	6480	2170	3450	3960	4490	4900
B-3	20.4	3250	5260	6350	7000	7400	2600	4410	5800	5700	6220	1760	2990	3660	4090	4500
B-4	23.0	3240	5430	5920	6690	7210	2400	4050	5570	5490	5840	1880	3060	3900	4010	4140
C-1	16.1	4320	7170	8540	9810	9840	3150	5240	7380	8180	8380	2150	3690	4760	5460	5940
C-2	20.6	4550	6940	8860	9250	9580	3140	5620	6850	7740	7850	1750	3380	4340	5010	5270
C-3	26.5	4000	6300	8320	9610	9700	2820	4540	6320	6850	7580	1880	3040	4260	4820	5380
C-4	33.3	3460	5680	7770	7940	7910	2300	3810	5600	5770	6560	1480	2470	3420	3850	4360
D-1	16.1	3990	5930	6870	7660	8660	2870	4620	5830	6480	7520	2240	3530	4070	4740	5430
D-2	20.3	3780	6160	8050	8530	9310	2810	4730	6040	6440	7280	2140	3780	4800	5230	5710
D-3	22.3	3850	6630	7460	8390	9020	2850	4780	6330	6790	7430	2010	3380	4740	4890	5790
D-4	25.6	3650	6160	7170	8130	9230	2560	4800	5880	6350	6700	1830	3400	4280	4680	5110
E-1	10.6	4930	7000	8300	9480	9630	4320	5920	7380	8360	8800	2930	4520	5790	5810	6660
E-2	15.3	4460	6780	7540	8430	10130	3890	5650	6930	7080	8270	2750	3650	4530	5220	6210
E-3	18.9	4690	6580	7250	8080	9480	3760	5720	6550	7210	8030	2760	4000	4330	5410	6810
E-4	23.7	4770	6580	7590	8400	9120	3330	4970	6280	6180	7860	2550	3480	4310	5440	5510
Average		3840	5070	7400	8030	8590	2930	4820	6140	6520	7220	2070	3390	4340	4770	5280

pressed in this manner is about the same as the usual 1:2:4; the exact equivalent of the latter will vary with the size and grading of the aggregate. This is the best method of expressing concrete mixtures. For ordinary mixtures the quantity of finished concrete is nearly equal to the volume of *mixed* aggregate. Wide variations are found if we attempt to compute yield of concrete in any other way, due to differences in total volume produced by mixing fine and coarse aggregates of widely different size and grading.

TABLE 10—COMPRESSION TESTS OF 6 BY 12-IN. CYLINDERS—SERIES 20.

Sand and pebble aggregate from Elgin, Ill., graded 0-1¼ in.
Specimens stored in damp sand; tested damp.
Each value is the average of 4 tests made on different days.
All strength values are given in pounds per square inch.

Cement.		1:2:4 Concrete.					1:3:5 Concrete.				
Ref. No.	Fineness, Residue on No. 200 Sieve.	7 d.	28 d.	3 mo.	6 mo.	1 yr.	7 d.	28 d.	3 mo.	6 mo.	1 yr.
A-1	12.5	1690	3050	4100	4310	5110	1100	1820	2800	3140	3620
A-2	16.9	1560	2530	3720	4080	4450	920	1570	2420	2870	3090
A-3	19.9	1310	2310	3710	3880	4410	740	1390	2300	2460	3260
A-4	22.9	1260	2370	3410	4180	4340	810	1480	2130	2790	2810
B-1	12.1	1890	3120	3980	4440	4920	1390	2130	2920	3340	3520
B-2	16.5	1880	3000	3960	4440	4570	1130	1970	2810	3020	3320
B-3	20.4	1670	2500	3630	3650	4540	930	1660	2210	2630	3080
B-4	23.0	1530	2470	3280	3720	3940	950	1630	2190	2360	2800
C-1	16.1	1990	3530	4780	5220	6020	1330	2400	3170	3810	4100
C-2	20.6	1970	3490	4700	5510	5800	1200	2350	3410	3470	3720
C-3	26.5	1750	3020	4300	4910	5360	1040	1770	2640	2880	3410
C-4	33.3	1300	2220	3460	4080	4760	840	1580	2180	2650	2930
D-1	16.1	1700	3220	4110	4410	5110	980	2130	2960	3350	3760
D-2	20.3	1790	3290	4090	4590	5330	1120	2310	3160	3490	3950
D-3	22.3	1600	3050	4100	4480	5220	1020	2080	2980	3440	3510
D-4	25.6	1440	2820	4050	4220	4890	990	2040	2520	3210	3610
E-1	10.6	2250	3420	5090	5180	5830	1660	2740	4030	4280	4930
E-2	15.3	2220	3220	4650	5070	5940	1400	2270	3450	3890	4310
E-3	18.9	2060	3410	4520	5070	5340	1550	2420	3180	3720	4170
E-4	23.7	1880	3030	4120	4630	5480	1300	2210	3280	3630	3770
Average		1740	2950	4090	4500	5070	1120	2000	2840	3220	3580

The 2 by 4-in. mortar cylinders used in several of the series were made in steel molds similar to those described above. Sufficient mortar was mixed to make 4 or 5 specimens; one from each batch was tested at each of the ages shown. The mortar was placed in the molds in 3 or 4 layers. These cylinders were stored in water and tested in a damp condition.

Briquette tests were made on all cements. The results of the tests on neat cement and sand mortars at ages of 7 days to 1 year are given in Tables 8, 12 and 17. The batches for the briquettes were mixed by hand in the manner described in the standard cement specifications. The batches were of such size that 4 or 5 briquettes could be made; one from each batch was tested at the ages shown. The mortar used in the 4 or 5

specimens in a set was mixed on different days. Briquettes were stored in water and tested wet.

The water content of the concrete is expressed in terms of the "relative consistency" or the "water-ratio." Relative consistency of 1.00 (normal consistency) is of such plasticity that the concrete of usual mixes will slump ½ to 1 in. if the metal form is withdrawn by a steady, up-

TABLE 11—QUANTITY OF MIXING WATER—SERIES 20.

Strength tests given in Tables 8, 9 and 10.

Ref. No.	Cement. Fineness, Residue on Sieve No. 100	Cement. Fineness, Residue on Sieve No. 200	Water—per cent by weight of Dry Materials. Neat.[1]	Sand Mortar.[2] 1:2	Sand Mortar.[2] 1:3	Sand Mortar.[2] 1:4	Ratio of Water to Volume of Cement. Neat.[1]	Sand Mortar.[2] 1:2	Sand Mortar.[2] 1:3	Sand Mortar.[2] 1:4	Concrete. 1:2:4	Concrete. 1:3:5
A-1	1.7	12.5	23.0	11.8	10.3	9.5	0.35	0.54	0.62	0.72	0.76	0.91
A-2	2.8	16.9	23.0	11.8	10.3	9.5	0.36	0.55	0.64	0.74	0.79	0.94
A-3	3.6	19.9	22.5	11.8	10.3	9.5	0.36	0.56	0.65	0.75	0.80	0.97
A-4	4.3	22.9	22.0	11.6	10.2	9.3	0.36	0.56	0.66	0.74	0.82	1.01
B-1	1.5	12.1	23.0	11.8	10.3	9.5	0.35	0.53	0.62	0.71	0.76	0.91
B-2	2.2	16.5	23.0	11.8	10.3	9.5	0.36	0.55	0.64	0.74	0.78	0.95
B-3	3.5	20.4	23.0	11.8	10.3	9.5	0.36	0.56	0.65	0.75	0.80	0.97
B-4	4.5	23.0	23.0	11.8	10.3	9.5	0.37	0.57	0.67	0.76	0.82	1.00
C-1	2.8	16.1	21.0	11.3	10.0	9.2	0.33	0.53	0.62	0.71	0.75	0.95
C-2	4.7	20.6	20.0	11.1	9.8	9.1	0.32	0.53	0.62	0.72	0.77	0.95
C-3	9.3	26.5	19.5	11.1	9.8	9.1	0.31	0.54	0.63	0.74	0.78	0.97
C-4	13.3	33.3	19.0	10.9	9.7	8.9	0.31	0.54	0.64	0.74	0.79	0.99
D-1	1.8	16.1	22.5	11.7	10.3	9.5	0.35	0.54	0.64	0.74	0.77	0.98
D-2	2.4	20.3	22.0	11.6	10.2	9.5	0.35	0.55	0.64	0.75	0.79	1.00
D-3	4.1	22.3	21.5	11.4	10.1	9.3	0.34	0.55	0.65	0.74	0.80	1.01
D-4	5.0	25.6	21.0	11.3	10.0	9.2	0.34	0.55	0.64	0.74	0.80	1.02
E-1	1.2	10.6	24.5	12.1	10.6	9.7	0.36	0.54	0.63	0.72	0.77	0.96
E-2	1.8	15.3	24.0	12.0	10.5	9.6	0.37	0.56	0.65	0.74	0.80	0.99
E-3	2.9	18.9	23.5	11.9	10.4	9.6	0.37	0.56	0.65	0.76	0.82	1.01
E-4	4.9	23.7	23.0	11.8	10.3	9.5	0.37	0.57	0.66	0.76	0.85	1.05

[1] Normal consistency of cement.
[2] Same amount of water used for Standard Ottawa and Elgin sand mortars.

ward pull immediately after molding the cylinder by the method described above. A relative consistency of 1.10 indicates that the concrete contains 10 per cent more water than that required for normal consistency, etc. The apparatus used in making the slump test is shown in Fig. 1. It consists of a framework carrying a 6 by 12-in. metal form on vertical guides and a windlass for lifting the form. The frame stands on leveling screws. The slump is measured from the original height of 12 in. to the top of the concrete after the removal of the form. A measuring rod enables the operator to determine the slump directly.*

*(Note added to Revised Edition, November, 1922.) Present practice in making the slump test for consistency or workability of concrete requires the use of a 4 by 8 by 12-in. truncated cone. For concrete of a given consistency the cone gives slumps about 2/3 that of the cylinder. The truncated cone is specified in the Progress Report of the Joint Committee on Standard Specifications for Concrete and Reinforced Concrete and is used in the Tentative Specifications for Workability of Concrete for Concrete Pavements of the American Society for Testing Materials.

Fig. 2 is a sketch showing the form taken by the concrete cylinders of different consistencies after the slump test. Slump tests were carried out on all specimens in Series 118 and 120. After the slump test was made the same concrete was remolded for the compression test.

The "water-ratio" is the ratio of volume of water to volume of cement in the batch. The weight of all cements was assumed as 94 lb. per cu. ft.

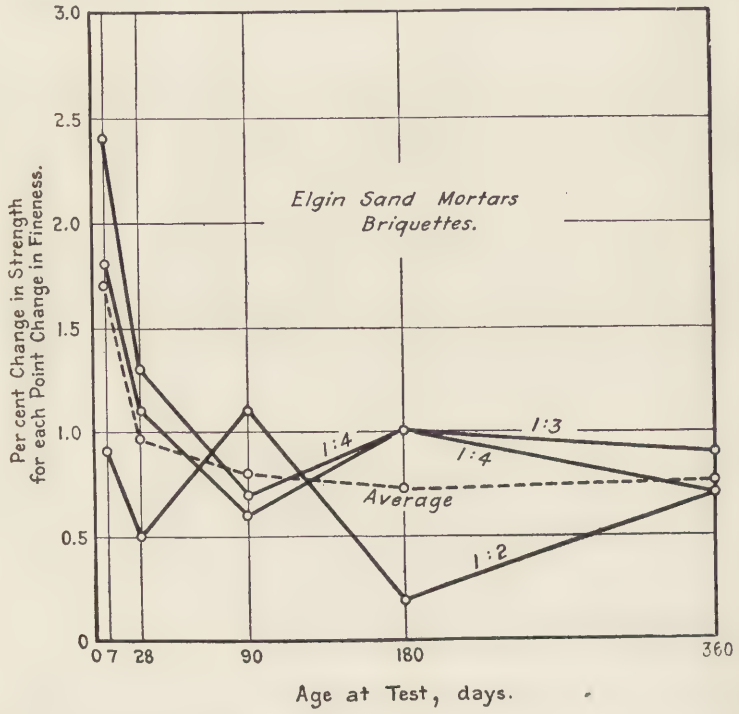


FIG. 5—CHANGE IN STRENGTH OF MORTAR WITH FINENESS OF CEMENT—SERIES 20.

Tension tests of briquettes. Compare Fig. 10.
Values are based on 80 tests; 16 each from 5 cements.

A rich mixture will give a low water-ratio and a lean mixture a high water-ratio. The distinction between the relative consistency and water-ratio should be made clear. The relative consistency refers to the *plastic condition* of the concrete without reference to the actual quantity of water as compared to the cement; while the water-ratio refers to the *actual quantity of water* as compared with the cement, and takes no account of the plasticity of the concrete.

In general, the 5 concrete test cylinders in a set were made on 5 different days. One specimen of each group was made before starting the second round. The strengths given in the tables are, therefore, the average of 5 entirely independent tests. In this way minor variations in materials, proportions, manipulation, etc., are eliminated.

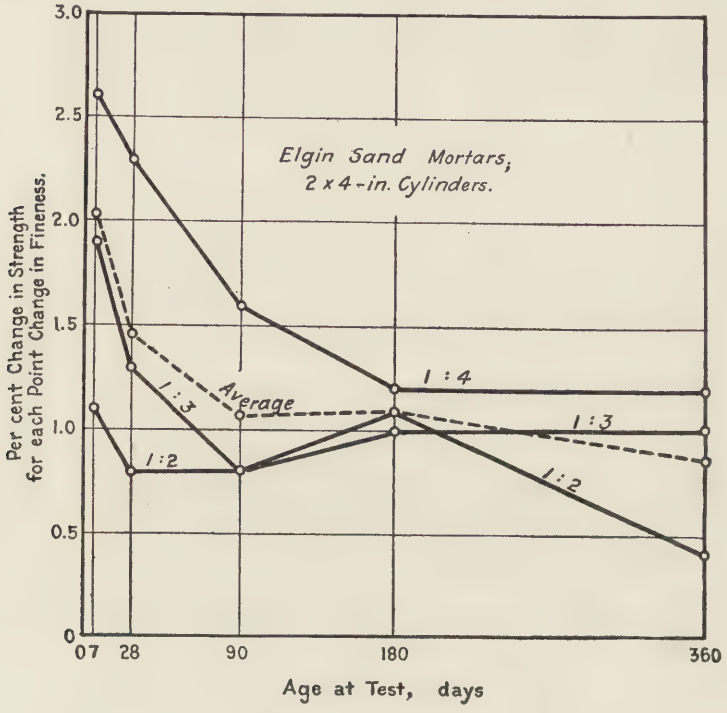


FIG. 6—CHANGE IN STRENGTH OF MORTAR WITH FINENESS OF CEMENT—SERIES 20.

Compression tests of 2 by 4-in. cylinders. Compare Fig. 10.
Values are based on 80 tests; 16 each from 5 cements.

METHODS OF TESTING.

The specimens for strength tests remained in damp sand or water until due to be tested; tests were made with specimens in wet or damp condition.

All tests of cement were carried out in accordance with the methods described in the Standard Specifications and Tests for Portland Cement

of the American Society for Testing Materials. Extreme care was taken in the determination of fineness, normal consistency, etc. In Series 31, 118 and 120 samples of cement were tested for fineness each day that a given cement was used. In this way an average of 15 to 18 tests was secured. Fineness tests were made with a mechanical sieve shaker. The sieves were calibrated by comparison with cement samples of standard fineness supplied by the Bureau of Standards.

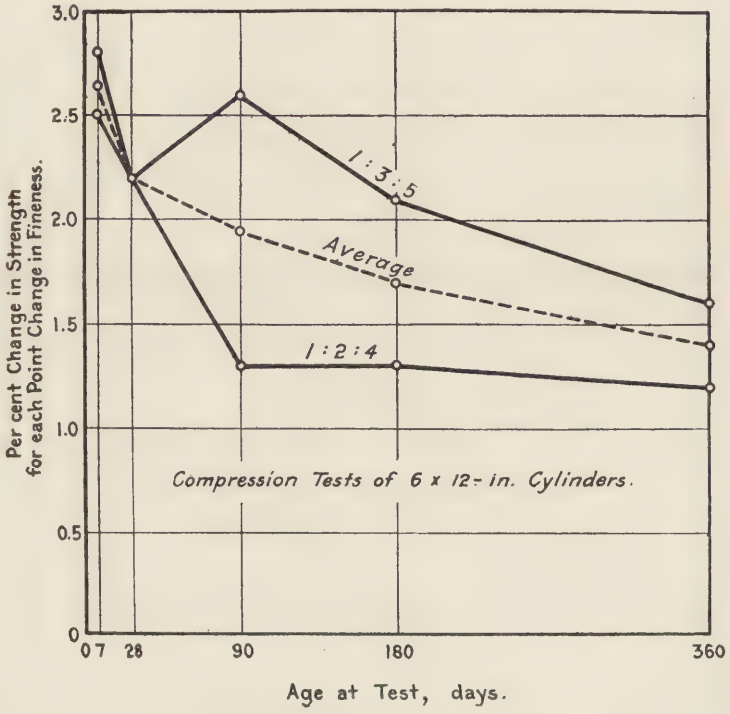


FIG. 7—CHANGE IN STRENGTH OF CONCRETE WITH FINENESS OF CEMENT—SERIES 20.

Compression tests of 6 by 12-in. cylinders. Compare Fig. 11.
Values are based on 80 tests; 16 each from 5 cements.

For Cements K and L used in Series 118 and 120 mechanical analyses were made by means of the air analyzer shown in Fig. 3. This apparatus was constructed on the same general principles followed in the analyzer designed by the Bureau of Standards, described in *Technologic Paper No. 48*, 1915. Our apparatus differs from the earlier analyzer in several important particulars:

TABLE 12—TENSION TESTS OF BRIQUETTES—SERIES 31.

Specimens stored in water; tested wet.
Each value is the average of 5 tests made on different days.
All strength values are given in pounds per square inch.

Cement.		Neat Cement.					1:3 Standard Sand Mortar.					1:3 Elgin Sand Mortar.				
Ref. No.	Fineness, Residue on No. 200 Sieve.	7 d.	28 d.	3 mo.	6 mo.	1 yr.	7 d.	28 d.	3 mo.	6 mo.	1 yr.	7 d.	28 d.	3 mo.	6 mo.	1 yr
F-1.....	4.9	532	500	490	476	456	335	435	486	425	375	436	499	570	607	564
F-2.....	8.7	569	522	545	520	400	310	418	454	425	360	403	540	595	656	512
F-3.....	14.2	566	565	590	596	472	295	383	433	392	355	401	448	531	565	521
F-4.....	17.9	596	632	636	556	443	294	362	409	391	346	327	431	533	546	528
F-5.....	24.5	609	677	650	640	570	262	312	376	369	312	311	402	489	527	458
F-6.....	28.1	587	685	684	590	562	228	335	342	309	312	291	390	406	487	461
F-7.....	33.4	587	664	682	698	594	239	302	329	299	268	292	341	377	457	388
G-1.....	2.2	500	548	504	466	435	311	416	457	424	364	380	497	570	609	527
G-2.....	7.9	522	610	590	554	506	276	423	442	443	367	331	478	522	586	478
G-3.....	12.9	589	662	676	660	521	289	395	449	404	406	369	468	585	591	569
G-4.....	19.9	568	644	621	632	502	282	343	451	350	359	334	447	530	553	517
G-5.....	25.2	559	624	684	672	509	257	347	376	359	307	279	373	461	536	492
G-6.....	29.6	603	638	756	622	571	248	337	383	358	322	306	416	471	545	498
G-7.....	34.0	534	650	728	718	627	235	287	352	315	288	282	366	400	475	466
H-1.....	12.0	606	594	618	586	489	316	435	432	421	382	393	491	596	542	549
H-2.....	19.9	487	716	734	669	550	254	404	470	440	395	285	444	566	602	532
H-3.....	23.3	632	670	732	648	601	301	445	452	368	341	325	476	543	552	529
H-4.....	25.1	704	702	668	748	648	292	413	419	361	336	332	454	531	556	514
H-5.....	30.1	702	746	794	676	615	266	384	384	312	331	302	426	483	485	440
Average.....		582	634	652	617	530	278	378	416	377	344	336	441	514	551	502

TABLE 13—COMPRESSION TESTS OF 2 BY 4-IN. MORTAR CYLINDERS—SERIES 31.

Specimens stored in water; tested wet.
Water-cement ratios are given in Table 15.
Each value is the average of 5 tests made on different days.
All strength values are given in pounds per square inch.

Cement.		1:3 Standard Sand Mortar.										1:3 Elgin Sand Mortar.				
		Made March, 1916.					Made August, 1916.					Made March, 1916.				
Ref. No.	Fineness, Residue on No. 200 Sieve.	7 d.	28 d.	3 mo.	6 mo.	1 yr.	7 d.	28 d.	3 mo.	6 mo.	1 yr.	7 d.	28 d.	3 mo.	6 mo.	1 yr.
F-1	4.9	3020	4770	5680	6330	5700	2590	4040	4970	5160	5860	3520	5620	6540	7000	7170
F-2	8.7	2860	4050	5040	5720	5570	2380	3890	4760	5060	5720	3620	5720	6530	7040	7130
F-3	14.2	2190	3580	4570	4680	4970	1990	3110	4020	4540	5150	2890	5050	6220	6720	6900
F-4	17.9	2090	3230	4020	4370	4890	2090	3240	4080	4560	5080	2910	4640	5880	6740	5720
F-5	24.5	1810	2890	3460	4110	4190	1880	3010	3890	4050	4520	2660	4380	5340	6030	6340
F-6	28.1	1740	2750	3610	3890	3310	1520	2520	3350	3560	3680	2260	4070	4890	5700	5720
F-7	33.4	1410	2160	3100	3220	3090	1480	2370	3100	3480	3360	2100	3410	4530	4850	5160
G-1	2.2	2490	3620	5250	5150	5300	2490	4070	5760	5750	6650	3090	4630	6220	6530	6060
G-2	7.9	1740	3190	4430	4300	4310	1940	3830	5100	4970	5580	2600	4480	5500	6250	6400
G-3	12.9	2010	3180	4780	4710	4620	1910	3600	4830	5020	5590	3240	5350	6770	7220	7560
G-4	19.9	1620	3070	4310	4070	4590	1780	3100	4010	4570	4760	2760	4510	5500	6210	6840
G-5	25.2	1660	2980	4010	4140	3870	1340	2400	3290	3770	4250	2500	4240	5660	5970	6310
G-6	29.6	1650	2640	4070	3710	3560	1500	2560	3510	3660	4360	2230	4090	5250	5660	6090
G-7	34.0	1350	2440	3410	3260	3180	1050	1990	2820	2960	3680	2150	3740	4400	5300	5490
H-1	12.0	2240	4070	4830	5020	5220	2290	3960	4770	4570	5590	3010	5710	6530	7040	6740
H-2	19.9	1800	3490	4260	4520	4560	2010	3320	4570	4500	5440	2410	4590	5530	6290	7030
H-3	23.3	1950	3400	3930	4210	4060	1900	3240	3800	4320	4970	2670	4610	5970	6140	6730
H-4	25.1	1980	3300	3800	3870	4000	1900	3060	3880	4230	4550	2570	4880	5850	6200	6570
H-5	30.1	1600	2680	3480	3440	3410	1620	2590	3640	3510	4050	1980	3730	4560	5120	5240
Average		1960	3240	4210	4350	4340	1880	3150	4110	4330	4890	2690	4600	5670	6210	6380

TABLE 14—COMPRESSION TESTS OF 6 BY 12-IN. CONCRETE CYLINDERS—SERIES 31.

Sand and pebble aggregate from Elgin, Ill., graded 0-1¼ in.
Water-cement ratios for concrete are given in Table 15.
Specimens stored in damp sand; tested damp.
Each value is the average of 5 tests made on different days.

Cement.		Compressive Strength, lb. per sq. in.																								
Ref. No.	Fineness Residue on 200 Sieve.	1:1½:3 Concrete.					1:1¾:3½ Concrete.					1:2:4 Concrete.					1:2½:5 Concrete.					1:3:6 Concrete.				
		7 d.	28 d.	3 mo.	6 mo.	1 yr.	7 d.	28 d.	3 mo.	6 mo.	1 yr.	7 d.	28 d.	3 mo.	6 mo.	1 yr.	7 d.	28 d.	3 mo.	6 mo.	1 yr.	7 d.	28 d.	3 mo.	6 mo.	1 yr.
F-1.	4.9	3200	4480	5680	6200	6300	2970	4420	5180	5600	6020	2600	3820	4780	5420	5540	2070	3270	4240	4550	4830	1370	2420	3160	3480	3690
F-2.	8.7	2910	4370	5430	5790	6010	2730	3920	4880	5520	5560	2350	3680	4580	5240	5280	1980	2970	3900	4260	4680	1270	2090	2910	3240	3440
F-3.	14.2	2570	3980	4980	5630	5800	2290	3620	4570	5090	5310	2010	3310	4130	4560	4680	1590	2580	3280	3860	4000	990	1760	2500	2820	3020
F-4.	17.9	2440	3720	4900	5540	5970	2150	3390	4470	4850	5330	1890	3010	4010	4610	4680	1450	2390	3210	3630	3780	970	1780	2450	2800	2910
F-5.	24.5	2140	3520	4420	5080	5470	1900	2970	4030	4520	4900	1540	2570	3430	4020	4260	1250	2060	2890	3240	3500	880	1480	2100	2410	2550
F-6.	28.1	1960	3170	4230	4850	5310	1620	2680	3550	4370	4320	1410	2290	3180	3470	4100	1110	1880	2610	2980	3320	780	1360	2010	2300	2420
F-7.	33.4	1670	2910	3860	4320	4770	1490	2490	3410	3790	4170	1230	2030	2960	3110	3670	990	1710	2390	2780	2950	640	1200	1790	1990	2160
G-1.	2.2	2880	4210	5320	5600	6100	2490	3850	4880	5470	5750	2420	3810	4830	5150	5240	1790	3060	4010	4420	4580	1130	1900	2970	3290	3550
G-2.	7.9	2290	3840	5030	5720	5910	2080	3530	4660	4990	5620	1970	3400	4410	4760	5020	1440	2590	3550	3890	4330	870	1610	2580	3060	3200
G-3.	12.9	2430	3990	5270	5560	5590	2080	3460	4670	5100	5330	1950	3200	4460	4850	4990	1370	2520	3450	3840	4160	870	1630	2530	2900	3150
G-4.	19.9	2020	3520	4660	5220	5340	1790	3180	4290	4510	4770	1650	2940	3980	4150	4820	1260	2320	3150	3480	3800	730	1480	2260	2510	2800
G-5.	25.2	1650	3130	4460	4930	5250	1450	2600	3700	4370	4690	1290	2490	3550	3930	4310	950	1810	2750	3100	3300	600	1130	1870	2170	2330
G-6.	29.6	1790	3130	4300	4940	5340	1610	2850	3880	4440	4660	1450	2490	3660	4030	4420	950	1750	2630	3100	3170	680	1250	1910	2280	2450
G-7.	34.0	1480	2670	3920	4430	4800	1230	2430	3470	4020	4170	1080	2000	3010	3540	3780	730	1450	2170	2550	2770	510	980	1600	1910	2090
H-1.	12.0	2180	4010	5430	6060	6460	2120	4070	5070	5770	6270	1740	3530	4690	5070	5500	1230	2710	3860	4200	4410	870	2010	2770	3130	3410
H-2.	19.9	1300	3360	4710	5160	5700	1090	3050	4390	5060	5490	1160	2590	3760	4350	4590	860	1960	2930	3380	3680	590	1390	2200	2560	2790
H-3.	23.3	2090	3780	4670	5210	5680	1740	3220	4230	5100	5310	1510	2900	3870	4320	4700	1030	2090	2990	3430	3700	750	1540	2370	2570	2790
H-4.	25.1	1990	3370	4330	5160	5560	1620	3100	4160	4670	5110	1500	2900	3680	4150	4640	1030	1950	2820	3220	3500	750	1430	2140	2470	2780
H-5.	30.1	1720	3090	3810	4290	4750	1540	2690	3640	4200	4710	1210	2190	3110	3560	3760	850	1620	2310	2720	3100	610	1150	1780	2150	2270
Average.....		2140	3590	4710	5250	5600	1890	3240	4280	4810	5230	1680	2910	3900	4340	4630	1260	2200	3120	3510	3780	840	1560	2310	2640	2830

1. Four separations may be made at once using the same air supply, and stacks and nozzles of different diameters;
2. The nozzles and stacks are of brass instead of glass;
3. The nozzles are fixed with reference to the stack;
4. The glass bulb is smaller and simpler in form.

TABLE 15—QUANTITY OF MIXING WATER—SERIES 31.

Strength tests given in Tables 12, 13 and 14.

Cement.		Water, per cent by weight of Dry Material.			Ratio of Water to Volume of Cement.							
		Mortar.			Mortar.			Concrete.				
Ref. No.	Fineness Residue on No. 200 Sieve.	Neat.[1]	1:3 St'd.	1:3 Elgin.	Neat.[1]	1:3 St'd.	1:3 Elgin.	1:1½:3	1:1¾:3½	1:2:4	1:2½:5	1:3:6
F-1.....	4.9	29.0	11.3	12.3	0.40	0.62	0.68	0.64	0.68	0.75	0.84	0.99
F-2.....	8.7	28.0	11.2	12.2	0.41	0.65	0.71	0.67	0.73	0.78	0.88	1.06
F-3.....	14.2	27.5	11.1	12.1	0.42	0.68	0.74	0.71	0.76	0.83	0.93	1.12
F-4.....	17.9	26.0	10.8	11.8	0.41	0.68	0.74	0.72	0.78	0.84	0.95	1.14
F-5.....	24.5	25.0	10.7	11.7	0.40	0.69	0.75	0.74	0.80	0.86	0.99	1.15
F-6.....	28.1	24.5	10.6	11.6	0.39	0.68	0.75	0.74	0.81	0.88	1.00	1.18
F-7.....	33.4	24.0	10.5	11.5	0.39	0.69	0.75	0.75	0.82	0.89	1.03	1.19
G-1.....	2.2	29.0	11.3	12.3	0.38	0.59	0.64	0.61	0.65	0.70	1.00	0.94
G-2.....	7.9	26.0	10.8	11.8	0.37	0.62	0.68	0.67	0.71	0.76	0.89	1.05
G-3.....	12.9	25.0	10.7	11.7	0.38	0.65	0.71	0.70	0.75	0.80	0.94	1.10
G-4.....	19.9	25.0	10.7	11.7	0.40	0.68	0.74	0.73	0.78	0.84	0.98	1.15
G-5.....	25.2	24.5	10.6	11.6	0.39	0.68	0.75	0.74	0.80	0.86	1.01	1.18
G-6.....	29.6	24.5	10.6	11.6	0.40	0.69	0.76	0.75	0.81	0.86	1.02	1.19
G-7.....	34.0	24.0	10.5	11.5	0.39	0.69	0.75	0.75	0.81	0.87	1.03	1.19
H-1.....	12.0	23.0	10.3	11.3	0.35	0.62	0.68	0.68	0.73	0.80	0.93	1.08
H-2.....	19.9	23.0	10.3	11.3	0.36	0.65	0.71	0.71	0.76	0.84	0.98	1.15
H-3.....	23.3	21.5	10.1	11.1	0.34	0.65	0.71	0.72	0.78	0.85	0.99	1.16
H-4.....	25.1	22.0	10.2	11.2	0.35	0.66	0.72	0.73	0.78	0.86	1.01	1.18
H-5.....	30.1	22.0	10.2	11.2	0.36	0.66	0.73	0.74	0.79	0.86	1.02	1.19

[1]Normal consistency of cement.

All stacks were 61 in. in length. Other dimensions are as follows:

UNIT.	INSIDE DIAMETER OF STACK, IN.	NOZZLE DIAMETER, IN.
A.....	2.62	0.130
B.....	2.86	0.100
C.....	3.12	0.070
D.....	3.37	0.040

Fifty-gram samples were used for Units A, B and C and 25-gram samples for Unit D. An air pressure of 1 lb. per sq. in. was used. The separation size of the units and the analyses of the cements are given in Table 5.

The unit weights of the cement and aggregate were determined by puddling the material in a machined cast-iron measure in the manner described above for molding the concrete test pieces. The cast-iron measures were cylindrical in form with inside diameter equal to depth. In general, a ⅕ cu. ft. measure was used.

The compression tests of mortar cylinders were made in a 40,000-lb. Riehlé testing machine. The test of 6 by 12-in. concrete cylinders were made in a 200,000-lb. Olsen machine. A spherical bearing block was used on top of the compression specimens during the test.

A special apparatus (Fig. 4) was designed and constructed for use in measuring the elongation and contraction of 6 by 12-in. cylinders. It consists essentially of a framework for holding the cylinder in an inclined position in V-shaped seats and means for accurate measurement of changes

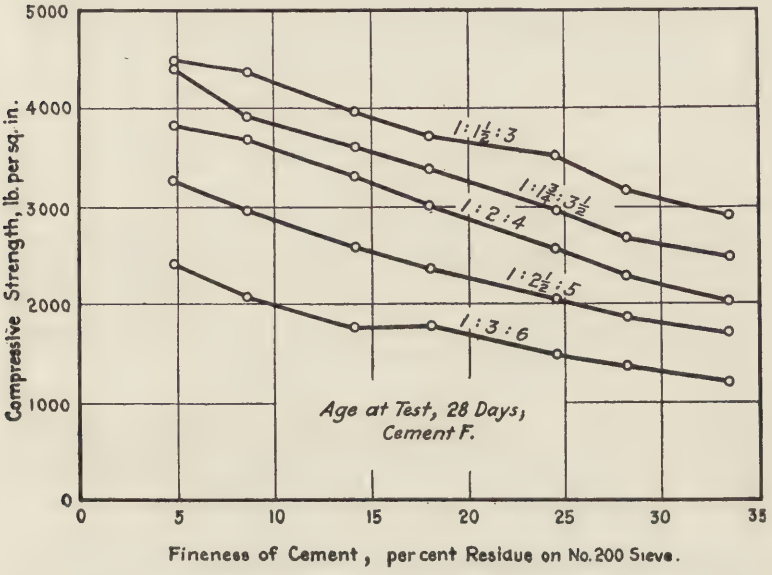


FIG. 8—EFFECT OF FINENESS OF CEMENT ON THE STRENGTH OF CONCRETE—SERIES 31.

Compression tests of 6 by 12-in. cylinders. See Table 14.

in length. The lower end of the cylinder rests against a 2-in. circular plate with a spherical seat. The change in length is measured by means of an Ames dial graduated to 0.001 in., which makes contact with the cylinder through a second 2-in. plate with spherical seat.

DISCUSSION OF TESTS.

The data of all tests referred to are given in the tables and diagrams. The data for each series are placed in a group for convenience of reference.

In this discussion most weight will be given to the compression tests of 6 by 12-in. cylinders. Tests of this kind were made in each series

with the exception of No. 60. The results are given in Tables 10, 14, 18, 23, 24 and 26. This report contains such a mass of data that the discussion will necessarily be confined to the more important features. The

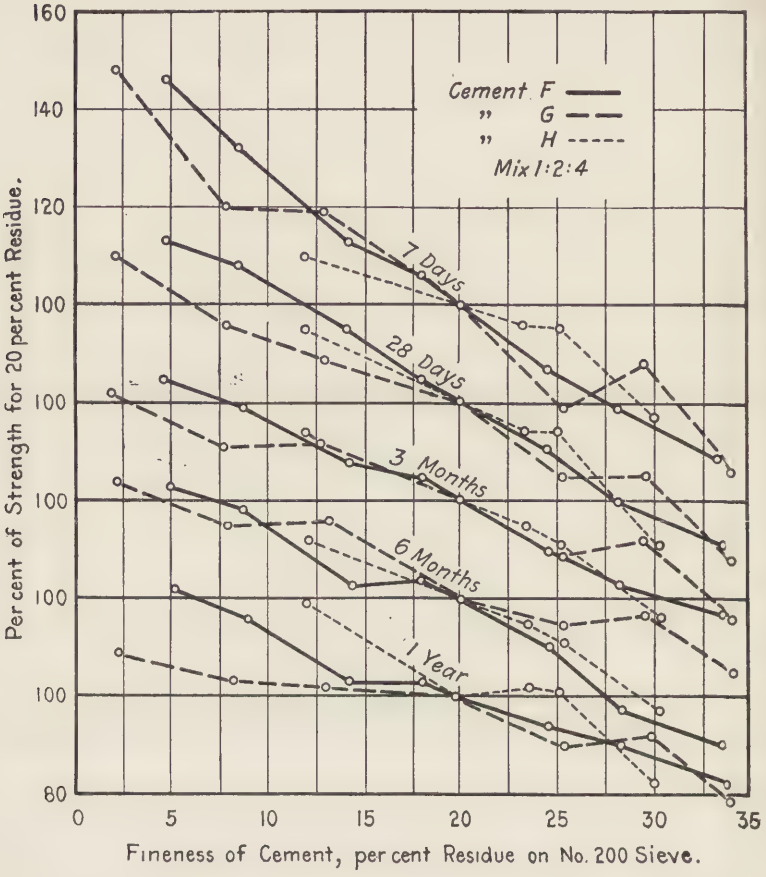


FIG. 9—EFFECT OF FINENESS OF CEMENT ON THE STRENGTH OF CONCRETE—SERIES 31.

Compression tests of 6 by 12-in. cylinders. See Table 14. Compare Fig. 18.

reader who is interested in certain details will find all necessary data for a more thorough study.

Effect of Fineness of Cement on the Strength of Concrete.—An examination of the tables and figures indicates that in general the strength of concrete increases with the fineness of cement. There are notable ex-

ceptions to this rule in the case of some of the cements having residues less than about 10 per cent on the No. 200 sieve.

The rate of change of strength of concrete with the fineness of the cement may be studied in several different ways. One method is illus-

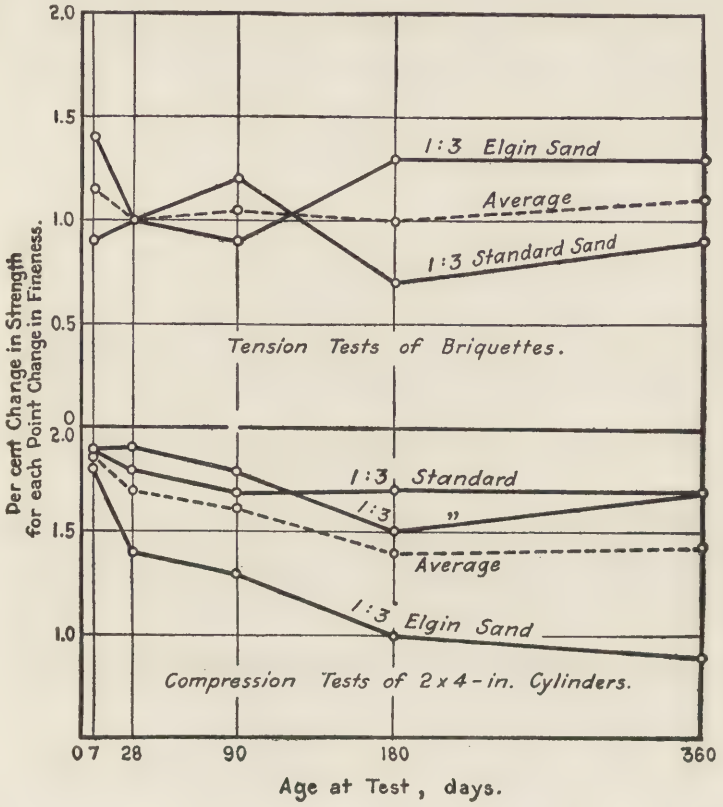


FIG. 10—CHANGE IN STRENGTH OF MORTAR WITH FINENESS OF CEMENT—SERIES 31.

Compare Fig. 5 and 6.
Each value is based on 95 tests; Cements F, G and H.

trated in Fig. 8 where the strength of the concrete for different mixtures has been platted against the fineness of the cement. In this instance only Cement F was platted; the other cements in this group give similar relations. It will be seen that the relation between the strength and fineness for the range of values covered may be represented by straight lines, which may be used to determine the percentage change in strength for

one fineness of cement as compared with another. In all of our calculations we have used the strength found for residue of 20 per cent as a basis of comparison. It will be seen that the percentage increase in strength for 1 per cent reduction in residue is considerably greater for the lean than for the rich mixtures.

Fig. 9 gives data similar to that found in Fig. 8 except that the values have been reduced to basis of 100 per cent for a residue of 20 per cent and the curves for Cements G and H have been added. While there is

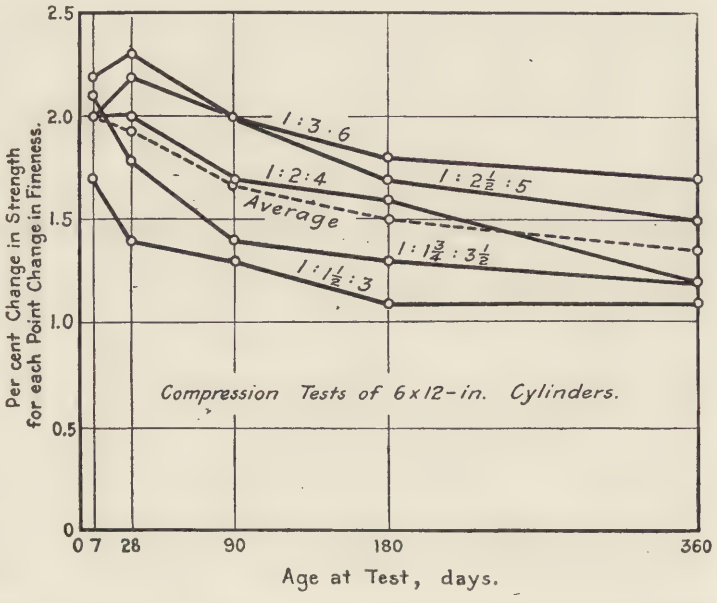


FIG. 11—CHANGE IN STRENGTH OF CONCRETE WITH FINENESS OF CEMENT—SERIES 31.

Compare Fig. 7.
Each value is based on 95 tests; Cements F, G and H.

a wide variation in the fineness covered by these cements, it will be noted that the values give roughly a straight-line relation. The slopes of the curves for Cement F are in general higher than the average, Cement G is lower than the average, and Cement H is about a mean between the other two. The slopes of the curves at 7 days are much greater than for other periods, indicating that finer grinding of the cement is more effective in increasing the early strength of the concrete than at subsequent periods. Similar diagrams for mortar tests made of sand of 6

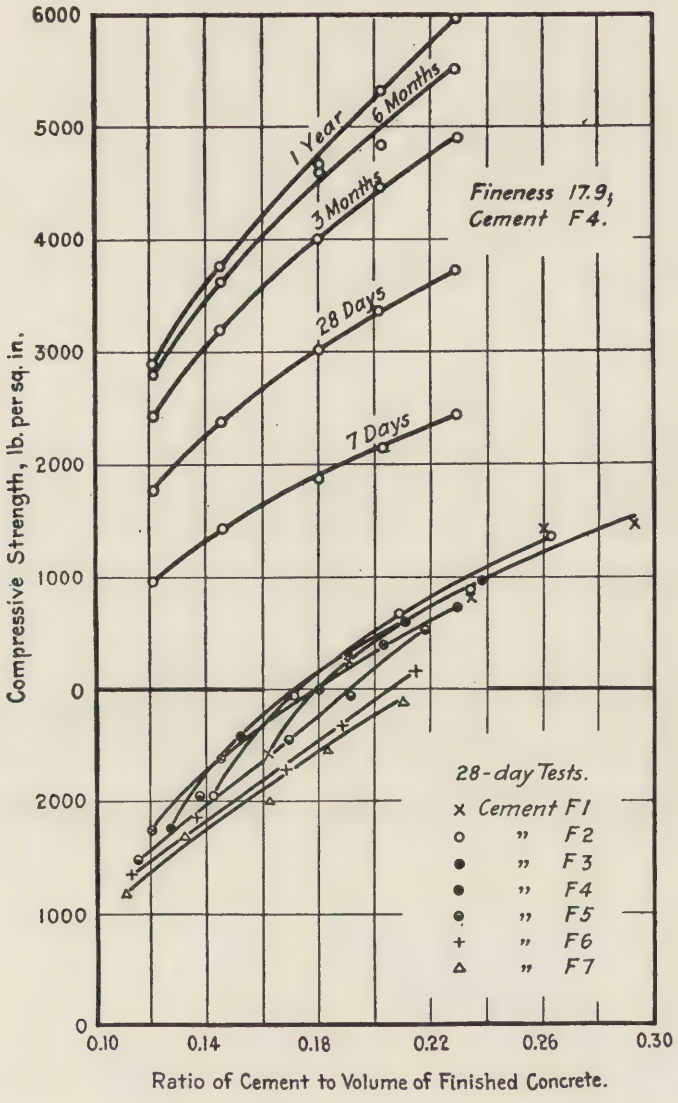


FIG. 12—EFFECT OF QUANTITY OF CEMENT ON THE STRENGTH OF CONCRETE—SERIES 31.

Compression tests of 6 by 12-in. cylinders. Data from Table 14.

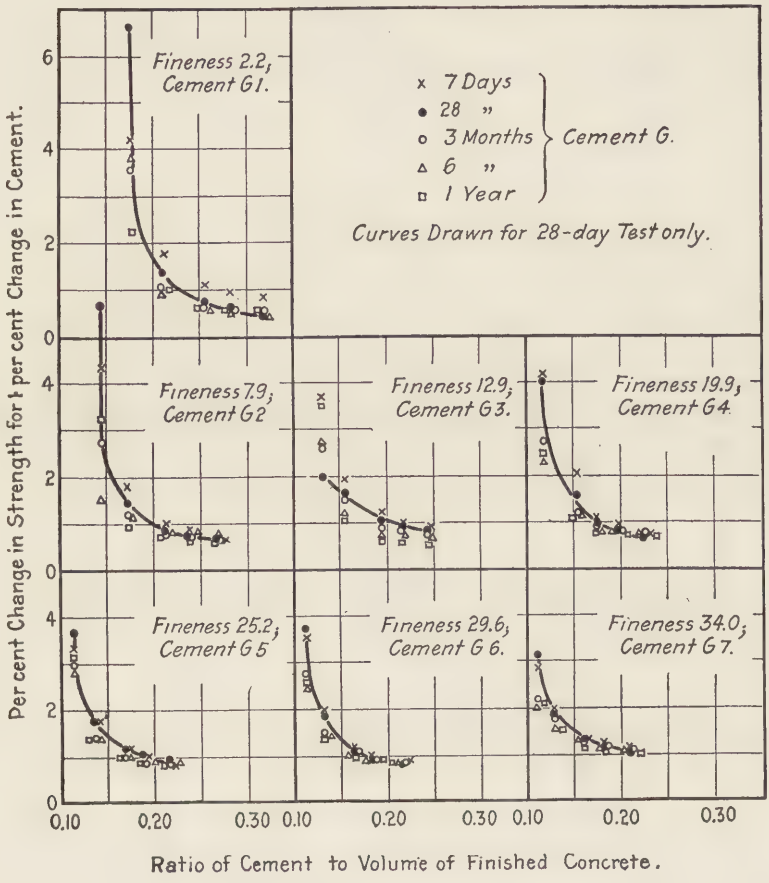


FIG. 13—RATE OF CHANGE IN STRENGTH OF CONCRETE WITH QUANTITY OF CEMENT—SERIES 31.

Compression tests of 6 by 12-in. cylinders. Cement G. Compare Fig. 14 and 36.

Values determined from curves similar to those in Fig. 12.

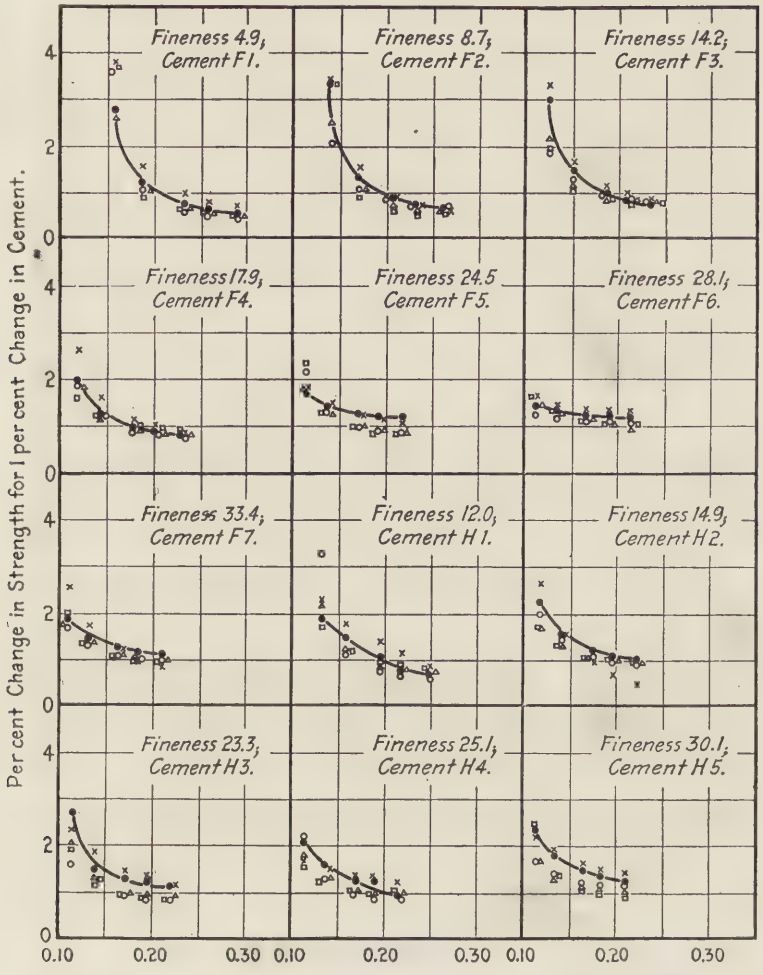


FIG. 14—RATE OF CHANGE IN STRENGTH OF CONCRETE WITH QUANTITY OF CEMENT—SERIES 31.

Compression tests of 6 by 12-in. cylinders. Cements F and H.
Compare Fig. 13 and 36.
Curves drawn for 28-day tests only.
Values determined from curves similar to those in Fig. 12.

different gradings at ages ranging from 7 days to 1 year are given in Fig. 16 to 18.

The relation between the strength of concrete and fineness of cement for Cements K and L in Series 118 and 120 is found in Fig. 21, 22, 23,

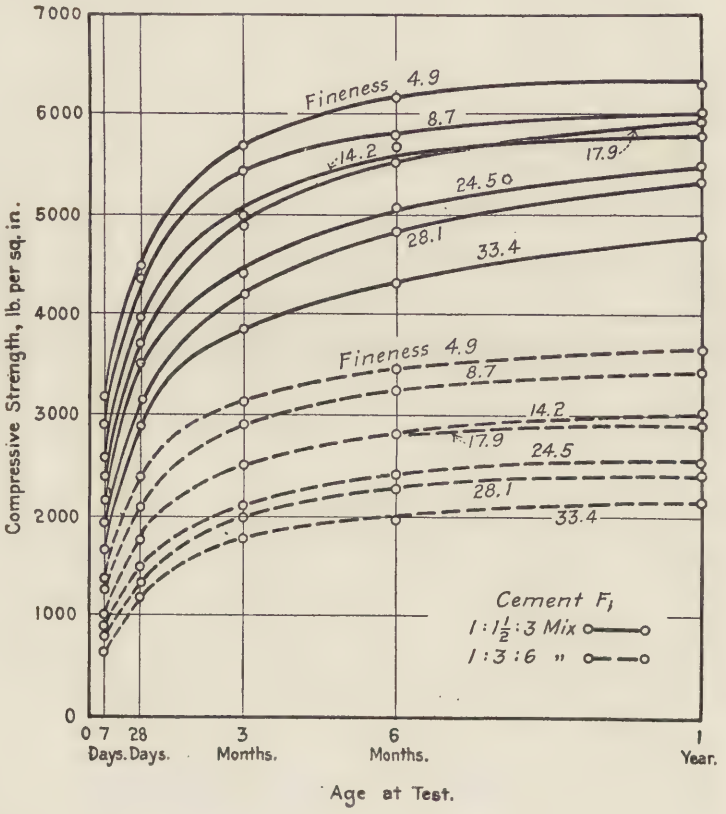


FIG. 15.—EFFECT OF AGE ON THE STRENGTH OF CONCRETE—SERIES 31.

Compression tests of 6 by 12-in. cylinders. See Table 14.

25 to 29. It will be noted that for all conditions of consistency, mix and size of aggregates the strength for Cement K falls off for the finest sample. The linear relation between fineness and strength is correct only for residues above 10 per cent for this cement.

For Cement L the strength of the samples having a residue of about

TABLE 16—EFFECT OF FINENESS OF CEMENT ON STRENGTH OF MORTAR—SERIES 60.

2 by 4-in. cylinders; stored in water; tested wet. Mix 1:2.55 by volume. Sand from Elgin, Ill.

Each value is the average of 5 tests made on different days.

Cement.			Water per cent by weight.	Compressive Strength, lb. per sq. in.					Relative Strength of Mortar.				
Ref. No.	Fineness Residue on No. 200 Sieve.	Normal Consistency.		7 d.	28 d.	3 mo.	6 mo.	1 yr.	7 d.	28 d.	3 mo.	6 mo.	1 yr.
SAND N-14. FINENESS MODULUS 4.44.													
F-1	4.9	26.0	10.5	4360	5920	6960	7280	8340	108	103	101	96	97
F-2	8.7	26.0	10.5	4480	6100	7120	7430	8070	111	107	103	98	93
F-3	14.2	24.5	10.2	4150	5810	6840	7280	8280	102	101	99	96	96
F-4	17.9	24.0	10.1	4130	5870	7000	7820	8820	102	103	102	103	102
F-5	24.5	23.0	9.9	3870	5420	6610	7030	8200	96	95	96	92	95
F-6	28.1	22.0	9.7	3350	4890	5890	6430	7520	83	85	86	84	87
F-7	33.4	22.0	9.7	3180	4560	5810	5840	7370	79	80	85	77	85
Average			10.1	3930	5510	6600	7020	8080					
SAND N-10. FINENESS MODULUS 4.06.													
F-1	4.9	26.0	10.9	4030	5790	6420	7120	8500	112	112	104	99	111
F-2	8.7	26.0	10.9	3890	5610	6320	7340	8030	108	109	102	103	105
F-3	14.2	24.5	10.6	3600	5330	6200	6410	8060	110	103	100	90	105
F-4	17.9	24.0	10.5	3730	5300	6490	7420	7990	104	103	105	105	104
F-5	24.5	23.0	10.2	3300	4860	5570	6660	6910	92	94	90	93	90
F-6	28.1	22.0	10.0	2690	4300	5620	5880	6530	75	83	91	82	85
F-7	33.4	22.0	10.0	2570	4100	4970	5320	6560	71	79	80	84	86
Average			10.4	3400	5040	5940	6590	7510					
SAND N-7. FINENESS MODULUS 3.63.													
F-1	4.9	26.0	11.3	3660	5080	6260	6860	7550	118	112	109	116	104
F-2	8.7	26.0	11.3	3380	4890	6180	6520	7170	109	108	108	111	99
F-3	14.2	24.5	11.0	3300	4830	5760	6060	6800	107	106	101	103	94
F-4	17.9	24.0	10.9	3190	4820	5930	6080	7480	103	106	103	103	103
F-5	24.5	23.0	10.7	2900	3930	5310	5520	6750	94	87	93	93	93
F-6	28.1	22.0	10.5	2210	3560	4370	5360	5730	71	78	76	91	79
F-7	33.4	22.0	10.5	2290	3370	4340	4780	5260	74	74	76	81	73
Average			10.9	2990	4350	5450	5880	6680					
SAND N-5. FINENESS MODULUS 3.17.													
F-1	4.9	26.0	11.9	3020	4470	5400	5850	6650	120	118	110	110	104
F-2	8.7	26.0	11.9	2890	4150	5480	6280	7110	115	109	112	118	112
F-3	14.2	24.5	11.6	2640	4070	5160	6040	6340	105	107	105	114	99
F-4	17.9	24.0	11.5	2660	3980	5230	5540	6690	106	105	107	104	105
F-5	24.5	23.0	11.3	2200	3420	4230	4820	5680	88	90	86	91	89
F-6	28.1	22.0	11.1	1790	2980	3960	4400	4860	71	78	81	83	76
F-7	33.4	22.0	11.1	1640	2760	3310	3690	4380	65	73	68	70	69
Average			11.5	2410	3690	4680	5230	5960					
SAND N-8. FINENESS MODULUS 3.00.													
F-1	4.9	26.0	12.3	3200	4750	5570	5800	6510	136	131	125	121	119
F-2	8.7	26.0	12.3	2840	4470	5610	5730	5910	121	123	126	119	108
F-3	14.2	24.5	12.0	2580	3920	4810	5020	5700	109	108	108	105	104
F-4	17.9	24.0	11.9	2470	3910	4700	5060	5720	105	108	105	106	105
F-5	24.5	23.0	11.7	2110	3040	3950	4290	4980	89	84	89	89	91
F-6	28.1	22.0	11.5	1670	2690	3480	3770	4330	71	74	78	78	79
F-7	33.4	22.0	11.5	1730	2500	3140	3410	4330	73	69	71	71	79
Average			11.9	2370	3610	4470	4730	5350					
SAND N-3. FINENESS MODULUS 2.53.													
F-1	4.9	26.0	12.8	2460	3930	4680	5400	6330	140	137	130	134	140
F-2	8.7	26.0	12.8	2370	3630	4750	5020	6010	135	127	132	125	133
F-3	14.2	24.5	12.5	2080	3250	3970	4520	5240	118	113	110	112	116
F-4	17.9	24.0	12.4	1810	3070	3830	4190	4960	103	107	106	103	109
F-5	24.5	23.0	12.1	1650	2420	3100	3630	3620	94	84	86	91	80
F-6	28.1	22.0	12.0	1360	2020	2800	3020	3900	77	70	78	75	86
F-7	33.4	22.0	12.0	1370	1920	2840	2860	3350	78	67	79	71	74
Average			12.4	1870	2890	3710	4090	4770					

7 per cent is abnormally high as compared with the other finenesses (see Fig. 29). These tests indicate that the extremely fine cements are likely to be erratic in their behavior. It will be pointed out below that the time of setting and the mortar strengths of the finest cements were also erratic.

The most useful basis for comparison in studying the effect of fine-

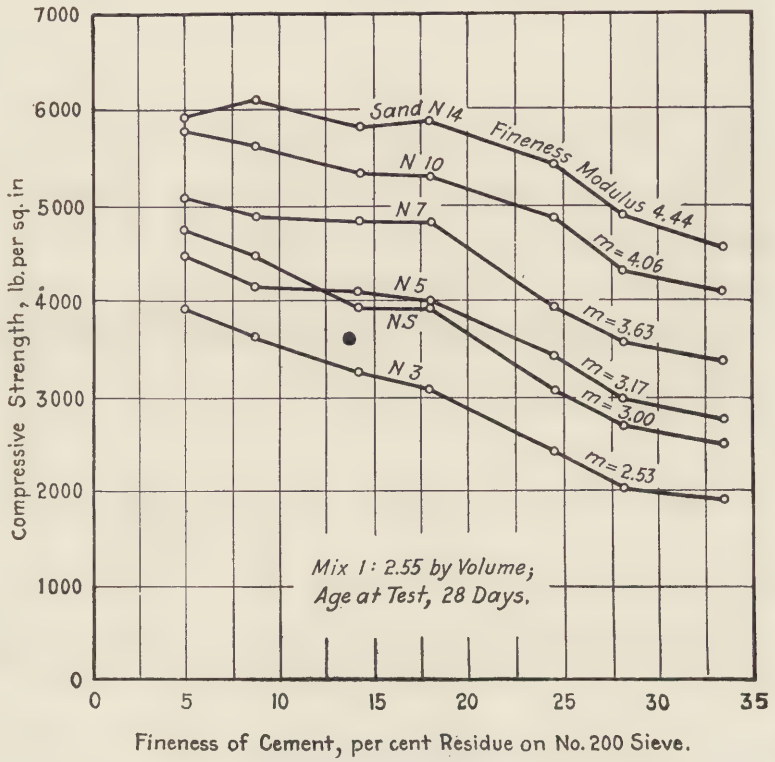


FIG. 16—EFFECT OF FINENESS OF CEMENT ON THE STRENGTH OF MORTAR—SERIES 60.

Compression tests of 2 by 4-in. cylinders. See Table 16.
Curves platted for 28-day tests only.

ness of cement is the percentage increase in strength of the concrete for 1 per cent reduction in residue on the No. 200 sieve. The values calculated from the slopes of the curves may be found for Series 20 and 31 in Fig. 7 and 11, and for Series 118 and 120, in Tables 20, 28 and 29.

The tests show that the lean mixtures are increased in strength relatively more than the rich ones for a given change in the fineness of the

cement. They also show that the beneficial effect of fine grinding tends to disappear with the age of the concrete.

The values in Tables 20 and 28 in which a wide range in consistencies was used, indicate that the change in strength due to fineness of cement

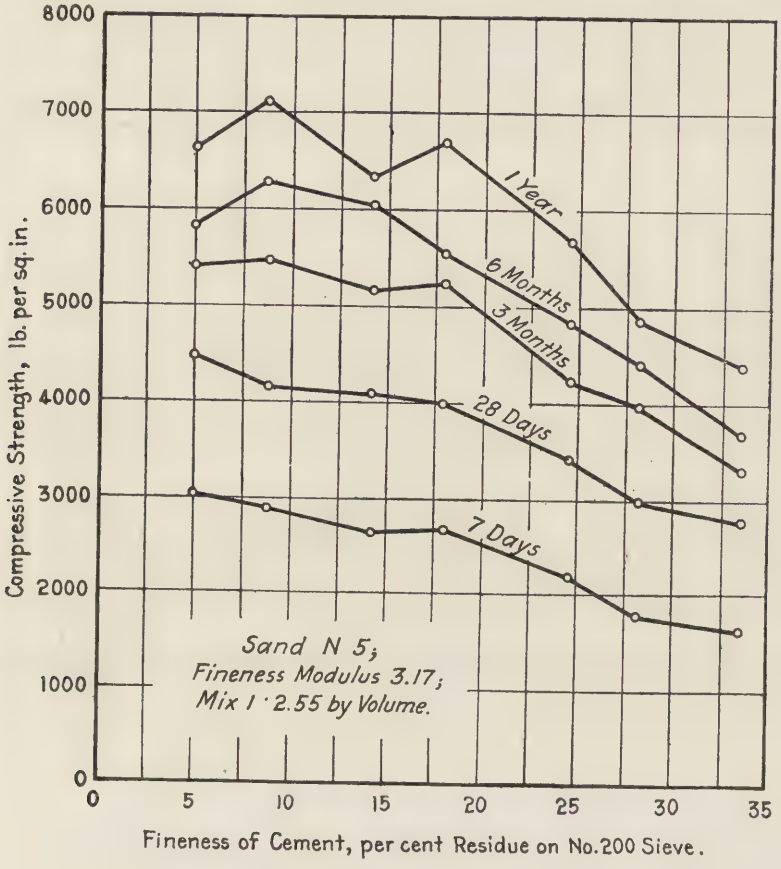


FIG. 17—EFFECT OF FINENESS OF CEMENT ON THE STRENGTH OF MORTAR—SERIES 60.

Compression tests of 2 by 4-in. cylinders. See Table 16.
Curves platted for Sand N-5 only.

is largely independent of the consistency of the concrete. An exception to this rule is found in the case of the very wet mixtures (relative consistency 2.00) where the rate of increase in strength was considerably lower than the average.

Effect of Fineness Using Different Cements.—An examination of the tables will show that there is no necessary relation between the fineness of cement and the strength of the resulting concrete so long as different

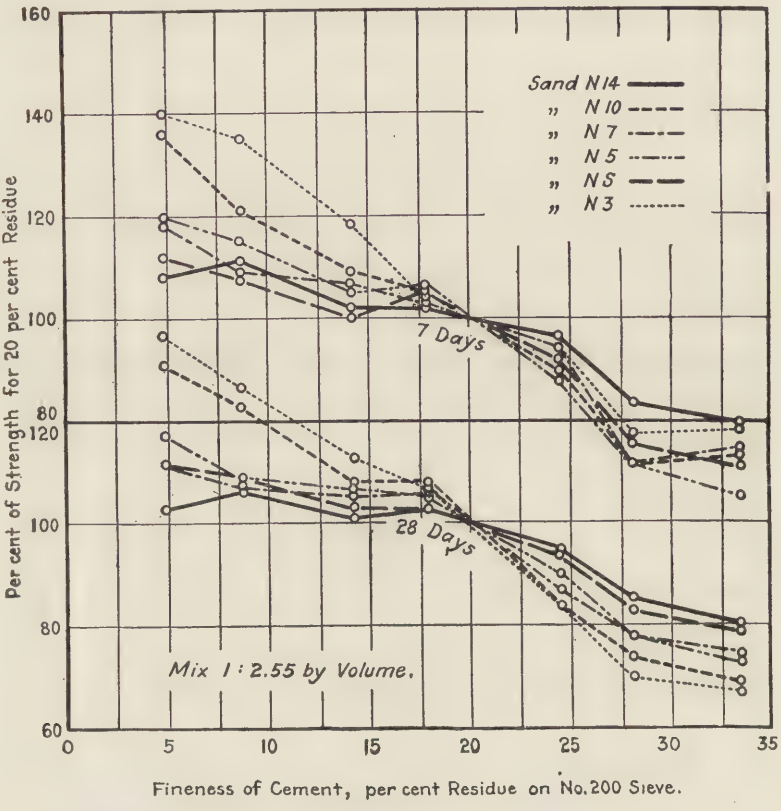


FIG. 18—EFFECT OF FINENESS OF CEMENT ON THE STRENGTH OF MORTAR—SERIES 60.

Compression tests of 2 by 4-in. cylinders. See Table 16. Compare Fig. 9.

cements are considered. For example, the strengths given by Cement L in Series 118 (Table 18) are only 40 to 60 per cent of those given by Cement K for the same mixtures. The coarsest samples for Cement K gave strengths comparable to the finest samples in Cement L. It is signifi-

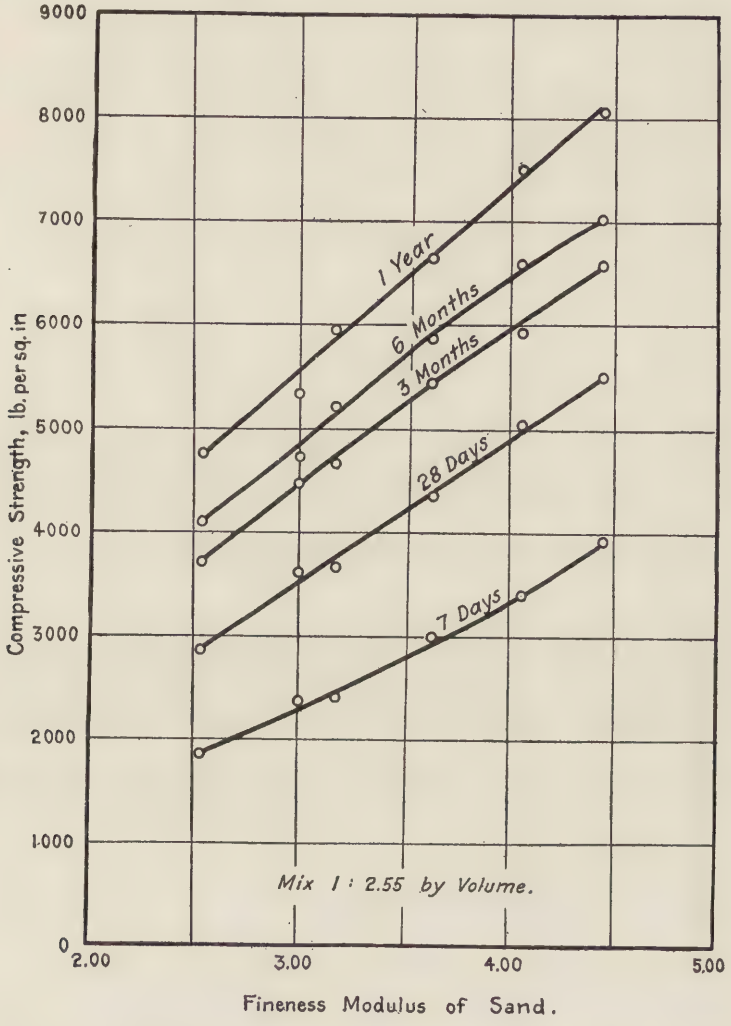


FIG. 19—EFFECT OF GRADING OF SAND ON THE STRENGTH OF MORTAR—SERIES 60.

Compression tests of 2 by 4-in. cylinders. See Table 16. Compare Fig. 34.

Values are the average of 35 tests from 7 finenesses of Cement F.

cant, however, that the rate of change in strength with fineness (Table 20) is not materially different.

Effect of Consistency of Concrete.—Concrete of a wide range in consistency was tested in Series 118 to 120. The effect of consistency on

TABLE 17—STRENGTH TESTS OF CEMENTS—SERIES 118 AND 120.

Mortar specimens were mixed to the consistency required by the standard specifications and methods of test of the American Society for Testing Materials.

Neat cement tests were made on paste of normal consistency.

Specimens stored in water; tested damp.

Each value is the average of 5 tests made on different days.

Cement.		2 by 4-in. Cylinders, Compressive Strength, lb. per sq. in.					Briquettes, Tensile Strength, lb. per sq. in.				
Ref. No.	Fineness Residue on No. 200 Sieve.	3 d.	7 d.	28 d.	3 mo.	1 yr.	3 d.	7 d.	28 d.	3 mo.	1 yr.
1:3 STANDARD SAND MORTAR.											
I-1	8.9	.....	900	2880	3760	4670	.....	158	268	401	350
I-2	13.9	.....	810	1730	3030	3570	.....	175	250	341	320
Av..	.....	.....	860	2300	3400	4120	.....	166	259	371	335
K-1	2.4	1630	2110	3370	4430	4850	222	275	370	427	377
K-2	9.4	1270	2270	3680	4290	4580	195	261	360	395	307
K-3	17.7	980	1520	2840	3430	3850	160	228	331	380	302
K-4	27.9	680	1050	1840	2810	2770	89	112	254	345	282
K-5	36.2	320	780	1390	1590	2060	40	65	190	295	183
Av..	.....	980	1550	2620	3310	3620	141	188	301	368	290
L-1	7.1	740	1640	3090	4400	5710	121	204	385	458	406
L-2	16.3	540	1220	2670	3100	4290	81	184	317	327	330
L-3	28.9	250	680	1280	1770	2040	65	104	227	276	250
L-4	32.3	200	460	1190	1450	1700	42	63	170	278	220
L-5	43.3	170	350	610	1250	1380	37	60	213	185	188
Av..	.....	380	870	1770	2390	3020	69	123	262	305	279
NEAT CEMENT.											
K-1	2.4	5030	6800	9470	9210	10370	486	600	551	558	503
K-2	9.4	7000	8180	12470	12380	14630	594	573	600	623	521
K-3	17.7	5800	8950	12580	12830	13960	440	617	612	682	598
K-4	27.9	3740	6730	10880	11800	13140	380	555	521	674	545
K-5	36.2	1540	5050	9240	10390	11680	185	530	673	698	600
Av..	.....	4620	7140	10930	11320	12750	417	575	591	647	553
L-1	7.1	4600	7150	11560	12900	14050	334	423	582	455	514
L-2	16.3	3600	5890	9120	11010	12670	358	416	605	564	600
L-3	28.9	1950	3940	7330	10140	13080	224	333	582	671	505
L-4	32.3	1510	3480	6950	9080	12850	202	321	601	559	538
L-5	43.	1340	2740	6000	9450	12360	180	261	601	664	576
Av..	.....	00	4640	6190	10520	13000	260	351	594	583	547

the strength for several mixtures is shown in Fig. 30. Similar diagrams may be constructed for other finenesses of both Cements K and L. The strength falls off rapidly as the quantity of mixing water is increased above "normal consistency." For a relative consistency of 1.50 the strength

is about one-half the maximum; for relative consistency 2.00, only 25 to 40 per cent of the maximum. In general, the strength falls off for mixtures drier than relative consistency 1.00. The richer mixtures are

TABLE 18—EFFECT OF FINENESS OF CEMENT ON THE STRENGTH OF CONCRETE—SERIES 118.

Compression tests of 6 by 12-in. cylinders.
Mix by volume.
Age at test, 28 days.
Specimens stored in damp sand; tested damp.
Each value is the average of 3 or 5 tests made on different days.
Weight of all cements assumed as 94 lb. per cu. ft. in proportioning.

Cement.		Compressive Strength, lb. per sq. in. for Different Consistencies.									
Ref. No.	Fineness, Residue on No. 200 Sieve.	0.95	1.00	1.05	1.10	1.15	1.20	1.25	1.50	2.00	Average.
AGGREGATE, CELITE, SAND AND BURNT SHALE SLAG—MIX 1:1¾.											
I-1	8.5	3670	4020	3330	3120	2890	2600	2160	1220	.....	280
I-2	13.9	3140	3120	2880	1940	2170	1350	1690	1320	.....	238
Average		3400	3570	3100	2530	2530	1980	1920	1270	.....	260
AGGREGATE, SAND AND PEBBLES—MIX 1:4.											
K-1	2.4	3240	2940	3200	3290	3030	3070	2580	1890	960	2690
K-2	9.4	3900	4020	3860	3630	3020	3290	2830	2100	1040	3080
K-3	17.7	3410	3690	3620	3270	2970	2490	2470	1610	1020	2730
K-4	27.9	2030	2420	2380	2050	1930	1920	1650	1210	820	1820
K-5	36.2	1360	1430	1640	1530	1500	1260	1310	1010	660	1300
Average		2790	2900	2940	2750	2490	2410	2170	1560	900	2320
AGGREGATE, CELITE, SAND AND CRUSHED BLAST-FURNACE SLAG—MIX 1:1¾.											
K-1	2.4	4780	4960	4800	4570	4290	4190	3910	2750	1600	3980
K-2	9.4	5070	4520	4840	4770	4800	4410	4270	3250	1740	4180
K-3	17.7	4240	4550	4700	4250	4060	4010	3840	3040	1540	3800
K-4	27.9	2730	3230	3210	3220	2770	2930	2680	1980	900	2630
K-5	36.2	2180	3130	2820	2580	2500	2580	2100	1520	810	2250
Average		3800	4080	4070	3880	3690	3620	3360	2510	1320	3370
L-1	7.1	3340	3320	3620	3300	3150	2620	2580	1760	910	2730
L-2	16.3	2600	3000	2760	2530	2350	2200	2270	1490	760	2220
L-3	28.9	1470	1990	2710	2550	2340	1940	2040	1310	700	1890
L-4	32.3	1180	1900	1930	2010	1810	1780	1790	1120	690	1580
L-5	43.3	1060	1380	1660	1610	1570	1460	1200	850	500	1250
Average		1930	2320	2540	2400	2240	2000	1980	1310	710	1930

more affected by increase in water than the lean ones. These tests confirm the results of earlier investigations made in this Laboratory.

The water-ratio has been found a convenient method of dealing with the relation between the water content and strength of concrete. The water-ratio is the ratio of the volume of water to the volume of cement in the batch. Our investigations indicate that this ratio may be used as

a measure of the strength of concrete for given materials and given test conditions, regardless of the mix, size or grading of the aggregate, or the relative consistency of the concrete, so long as the concrete is plastic and the aggregate is not too coarse for the quantity of cement used. Typical examples of the water-ratio-strength relation from these tests may

TABLE 19—QUANTITY OF MIXING WATER IN CONCRETE—SERIES 118.

Strength tests given in Table 18.

Water reported on basis of true volume of cement, that is, the differences in unit weights of the cements are taken into account. The quantity of mixing water for a given mix and consistency would be constant were it not for (1) different normal consistencies in the cement and (2) different unit weights of cement.

Cement.		Ratio of Water to Volume of Cement for Different Consistencies.								
Ref. No.	Fineness, Residue on No. 200 Sieve.	0.95	1.00	1.05	1.10	1.15	1.20	1.25	1.50	2.00
AGGREGATES, CELITE, SAND AND BURNT SHALE SLAG—MIX 1:1¾.										
I-1....	8.5	0.676	0.712	0.748	0.783	0.819	0.855	0.891	1.070	.....
I-2....	13.9	0.705	0.742	0.777	0.815	0.852	0.890	0.927	1.112	.....
AGGREGATES, SAND AND PEBBLES FROM ELGIN, ILL.—MIX 1:4										
K-1...	2.4	0.644	0.675	0.712	0.744	0.778	0.814	0.845	1.015	1.353
K-2...	9.4	0.691	0.725	0.763	0.799	0.834	0.872	0.907	1.087	1.450
K-3...	17.7	0.740	0.778	0.817	0.858	0.896	0.933	0.975	1.170	1.558
K-4...	27.9	0.810	0.850	0.896	0.938	0.980	1.024	1.067	1.280	1.704
K-5...	36.2	0.830	0.873	0.916	0.962	1.005	1.048	1.091	1.313	1.748
AGGREGATES, CELITE, SAND AND CRUSHED BLAST-FURNACE SLAG—MIX 1:1¾.										
K-1...	2.4	0.528	0.555	0.584	0.610	0.639	0.668	0.695	0.835	1.113
K-2...	9.4	0.562	0.591	0.620	0.649	0.679	0.710	0.738	0.888	1.183
K-3...	17.7	0.603	0.634	0.664	0.696	0.728	0.758	0.792	0.948	1.268
K-4...	27.9	0.656	0.692	0.727	0.762	0.797	0.832	0.865	1.038	1.383
K-5...	36.2	0.675	0.713	0.748	0.783	0.823	0.855	0.890	1.068	1.428
L-1...	7.1	0.546	0.576	0.603	0.631	0.661	0.689	0.718	0.863	1.148
L-2...	15.3	0.598	0.632	0.662	0.692	0.725	0.755	0.787	0.946	1.260
L-3...	28.9	0.635	0.671	0.705	0.737	0.770	0.807	0.838	1.005	1.340
L-4...	32.3	0.665	0.697	0.730	0.765	0.800	0.835	0.874	1.047	1.390
L-5...	43.3	0.665	0.700	0.733	0.768	0.803	0.837	0.873	1.047	1.400

be found in Fig. 31 and 32. Diagrams of the same form may be constructed for the other fineness from data given in Tables 23 to 25. The curves drawn in Fig. 32 were constructed from diagrams similar to Fig. 31 for other finenesses of Cement K. It will be noted that a single water-ratio-strength curve in Fig. 31 represents the tests covered by 6 curves in Fig. 30, except that the low strengths due to abnormally dry concrete have been omitted. The simplicity of the relation brought out in Fig. 31 would not be recognized from a study of the curves in Fig. 30.

The water-ratio - strength relation is of the same form, regardless of the fineness of the cement. The relation may be expressed by the equation,

$$S = \frac{D}{X^a}$$

where S is the compressive strength of the concrete, X is the water-ratio, and D and a are constants whose values depend on the quality of cement and the conditions of the test. Typical values of the constants D and a are given in Fig. 32. It should be noted that a is an exponent.

TABLE 20—CHANGE IN STRENGTH OF CONCRETE WITH FINENESS OF CEMENT—SERIES 118.

(EFFECT OF CONSISTENCY.)

Data from compression tests of 6 by 12-in. cylinders. (For details of tests see Table 18.)

The strength of concrete increases with the fineness of the cement; reducing the residue on the No. 200 sieve by 1 point increases the strength by the percentages shown.

No attempt was made to calculate values for Cement I, since the two samples were not from the same lot and gave a narrow range in fineness.

Cement.	Mix by Volume.	Age at Test, days.	Change in Strength of Concrete for Each Point Change in Fineness of Cement; Per Cent of Strength for 20 per cent Residue.									
			0.95[a]	1.00	1.05	1.10	1.15	1.20	1.25	1.50	2.00	Average.
AGGREGATES, SAND AND PEBBLES FROM ELGIN, ILL.												
K.....	1:4	28	3.3	3.5	3.1	3.1	2.7	2.7	2.7	2.5	2.1	2.9
AGGREGATES, CELITE, SAND AND CRUSHED BLAST-FURNACE SLAG.												
K.....	1:1¾	28	3.0	1.8	2.3	2.0	2.7	2.2	2.1	2.8	2.8	2.4
L.....	1:1¾	28	3.3	2.2	2.1	1.8	1.7	1.4	2.0	2.1	1.3	1.9
Grand Average.....			3.2	2.5	2.5	2.3	2.4	2.1	2.3	2.5	2.1	2.4

[a] Relative consistency of concrete.

Our report on "Design of Concrete Mixtures" [1] gave a somewhat different equation for this relation. For usual ranges of concrete mixtures both forms of equation give similar results; for the wetter consistencies the above equation gives somewhat higher values than the earlier equation. However, it should be understood that the exact type of the algebraic equation is not important. The essential feature is that the water content of the concrete measured in terms of the volume of the cement (the water-ratio) is the determining factor in fixing the strength of concrete made from given materials. In constructing an equation of this kind we are

[1] *Bulletin 1*, Structural Materials Research Laboratory, Lewis Institute.

simply deriving the equation of a curve which most nearly represents the experimental values. It is obvious that equations of many different types may be used.

TABLE 21—SLUMP TESTS FOR WORKABILITY OF CONCRETE—SERIES 118.

Tests made on 6 by 12-in. cylinders.

The slump test was made by molding a 6 by 12-in. cylinder by puddling with a ⅝-in. steel bar, then withdrawing the metal form by a steady upward pull. The shortening of the fresh concrete is measured in inches. This is the "slump." The apparatus used for lifting the form is shown in Fig. 1.

Each value is the average of 3 or 5 tests made on different days.

Cement.		Slump for Different Consistencies, in.								
Ref. No.	Fineness, Residue on No. 200 Sieve.	0.95	1.00	1.05	1.10	1.15	1.20	1.25	1.50	Average.
AGGREGATES, CELITE, SAND AND BURNT SHALE SLAG—MIX 1:1¾.										
I-1....	8.5	0.4	1.4	2.3	3.3	4.7	7.0	7.3	10.1	4.3
I-2....	13.9	0.6	1.6	3.6	6.2	7.7	8.7	9.0	10.7	5.8
Average.....		0.5	1.5	3.0	4.8	6.2	7.8	8.2	10.4	5.0
AGGREGATES, SAND AND PEBBLES FROM ELGIN, ILL.—MIX 1:4.										
K-1...	2.4	0.8	1.3	3.7	5.8	7.1	8.3	9.0	10.1	5.8
K-2...	9.4	0.7	1.8	4.7	7.2	8.5	8.4	8.8	9.8	6.2
K-3...	17.7	0.4	0.8	2.4	6.9	7.7	8.1	8.6	9.7	5.6
K-4...	27.9	0.2	0.4	1.2	5.9	7.7	7.4	8.1	9.2	5.0
K-5...	36.2	0.2	0.3	0.4	0.7	2.3	6.4	7.1	8.9	3.3
Average.....		0.5	0.9	2.5	5.3	6.7	7.7	8.3	9.5	5.2
AGGREGATES, CELITE, SAND AND CRUSHED BLAST FURNACE SLAG—MIX. 1:1¾.										
K-1...	2.4	0.4	0.9	1.6	3.2	4.1	5.7	6.9	9.6	4.0
K-2...	9.4	0.5	0.9	2.0	3.3	4.9	6.9	7.9	10.5	4.6
K-3...	17.7	0.4	0.7	1.6	3.4	5.2	7.2	8.0	10.2	4.6
K-4...	27.9	0.3	0.7	1.3	3.1	5.3	6.9	7.8	10.1	4.4
K-5...	36.2	0.3	0.8	1.2	2.3	4.9	6.6	7.7	10.1	4.2
Average.....		0.4	0.8	1.5	3.1	4.9	6.7	7.7	10.1	4.4
L-1...	7.1	0.4	0.9	2.2	3.3	4.9	6.8	8.4	10.4	4.7
L-2...	15.3	0.3	0.8	1.7	3.1	4.2	6.5	7.2	10.0	4.2
L-3...	28.9	0.2	0.5	0.9	2.6	4.3	6.5	7.5	10.4	4.1
L-4...	32.3	0.2	0.4	0.8	1.3	3.8	6.5	7.1	10.1	3.8
L-5...	43.3	0.2	0.3	0.6	1.2	2.0	5.7	7.0	9.8	3.4
Average.....		0.3	0.6	1.2	2.3	3.8	6.4	7.4	10.1	4.0

The values given in Table 28 indicate that the consistency of the concrete has little influence on the rate of change of strength due to fineness of grinding of the cement. There is an exception to this conclusion in the case of the very wet mixtures, in which the benefit of fine grinding is somewhat reduced.

Quantity of Cement.—The effect of fineness of cement was studied in a wide range of mixes. Series 20 included 2 concrete mixtures; Series 31, 5 mixtures; Series 118, 2 mixtures; Series 120, 6 mixtures, ranging from 1:10 to 1:2. The mortar tests included mixtures up to neat cement.

TABLE 22*a*—EFFECT OF FINENESS OF CEMENT ON THE YIELD OF CONCRETE—SERIES 118.

6 by 12-in. cylinders.
Yield is the volume of concrete produced by one volume of mixed aggregate.
Density is the total solid material in the mass.
Weights were determined immediately on removal from the forms.
Each value is the average of 3 or 5 tests made on different days.

Cement.		Relative Consistency of Concrete.									
Ref. No.	Fineness, Residue on No. 200 Sieve.	0.95	1.00	1.05	1.10	1.15	1.20	1.25	1.50	2.00	Average.
AGGREGATES, CELITE, SAND AND BURNT SHALE SLAG—MIX 1:1¾.											
I-1	8.5	1.322	1.356	1.380	1.405	1.418	1.442	1.439	1.527	.....	1.411
I-2	13.9	.....	1.318	1.341	1.363	1.399	1.413	1.411	1.468	.....	1.388
Average		1.322	1.337	1.360	1.384	1.408	1.427	1.425	1.497		1.399
AGGREGATES, SAND AND PEBBLES FROM ELGIN, ILL.—MIX 1:4.											
K-1	2.4	1.079	1.090	1.093	1.106	1.118	1.108	1.127	1.157	1.193	1.119
K-2	9.4	1.076	1.080	1.091	1.089	1.093	1.097	1.102	1.130	1.180	1.104
K-3	17.7	1.090	1.087	1.083	1.094	1.092	1.104	1.107	1.144	1.178	1.109
K-4	27.9	1.127	1.093	1.090	1.103	1.099	1.110	1.115	1.143	1.193	1.119
K-5	36.2	1.134	1.121	1.112	1.100	1.113	1.117	1.120	1.149	1.183	1.128
Average		1.101	1.094	1.094	1.098	1.103	1.107	1.114	1.145	1.185	1.116
AGGREGATES, CELITE, SAND AND CRUSHED BLAST-FURNACE SLAG—MIX 1:1¾.											
K-1	2.4	1.361	1.350	1.359	1.387	1.396	1.416	1.426	1.503	1.621	1.424
K-2	9.4	1.334	1.333	1.332	1.350	1.369	1.378	1.384	1.438	1.570	1.388
K-3	17.7	1.332	1.321	1.330	1.347	1.356	1.374	1.382	1.435	1.540	1.380
K-4	27.9	1.382	1.350	1.358	1.347	1.354	1.372	1.392	1.453	1.540	1.394
K-5	36.2	1.369	1.319	1.357	1.346	1.363	1.372	1.388	1.442	1.550	1.390
Average		1.340	1.335	1.347	1.355	1.368	1.382	1.394	1.454	1.564	1.395
L-1	7.1	1.363	1.324	1.341	1.350	1.369	1.386	1.394	1.470	1.569	1.396
L-2	16.3	1.352	1.321	1.348	1.356	1.364	1.383	1.402	1.444	1.540	1.390
L-3	28.9	1.420	1.366	1.344	1.333	1.350	1.379	1.388	1.439	1.543	1.396
L-4	32.3	1.440	1.363	1.342	1.340	1.358	1.367	1.385	1.435	1.540	1.397
L-5	43.3	1.423	1.359	1.328	1.325	1.333	1.350	1.380	1.437	1.517	1.384
Average		1.400	1.347	1.341	1.355	1.355	1.373	1.390	1.445	1.542	1.393

The curves in Fig. 12 and 35 shows the effect of quantity of cement for typical cements. The cement is expressed in terms of the volume of the finished concrete. The rate of change in strength with cement can be calculated from the slopes of these curves. Rates calculated in this way have been platted from Series 120 in Fig. 36, and from Series 31 in Fig.

13 and 14. For a given plastic condition the strength of concrete increased with the quantity of cement for all finenesses and consistencies. The rate of increase is higher for the lean than for the rich mixes, and is practically independent of the consistency of the concrete. It is higher at early periods than at later ages. The fineness of cement has little or no effect on the rate of increase in strength of concrete due to a given in-

TABLE 22*b*—EFFECT OF FINENESS OF CEMENT ON THE DENSITY OF CONCRETE—SERIES 118.

Cement.		Relative Consistency of Concrete.									
Ref. No.	Fineness, Residue on No. 200 Sieve	0.95	1.00	1.05	1.10	1.15	1.20	1.25	1.50	2.00	Average
AGGREGATES, CELITE, SAND AND BURNT SHALE SLAG—MIX 1:1¾.											
I-1	8.5	0.684	0.667	0.655	0.643	0.637	0.627	0.628	0.592	.....	0.642
I-2	13.9	.....	0.686	0.674	0.664	0.646	0.640	0.641	0.616	.....	0.652
Average		0.684	0.676	0.664	0.653	0.642	0.633	0.634	0.604	.....	0.647
AGGREGATES, SAND AND PEBBLES FROM ELGIN, ILL.—MIX 1:4.											
K-1	2.4	0.817	0.808	0.806	0.798	0.789	0.796	0.782	0.762	0.739	0.788
K-2	9.4	0.820	0.816	0.808	0.810	0.806	0.804	0.800	0.780	0.747	0.799
K-3	17.7	0.809	0.812	0.814	0.805	0.807	0.799	0.797	0.770	0.749	0.796
K-4	27.9	0.783	0.807	0.809	0.799	0.803	0.795	0.791	0.772	0.739	0.789
K-5	36.2	0.777	0.787	0.792	0.802	0.792	0.790	0.788	0.768	0.745	0.782
Average		0.801	0.806	0.806	0.803	0.799	0.797	0.792	0.770	0.744	0.791
AGGREGATES, CELITE, SAND AND CRUSHED BLAST FURNACE SLAG—MIX 1:1¾.											
K-1	2.4	0.739	0.745	0.740	0.726	0.721	0.711	0.705	0.669	0.621	0.708
K-2	9.4	0.754	0.755	0.756	0.746	0.735	0.731	0.727	0.700	0.641	0.727
K-3	17.7	0.755	0.762	0.757	0.748	0.743	0.732	0.728	0.702	0.653	0.731
K-4	27.9	0.728	0.745	0.741	0.747	0.743	0.733	0.722	0.692	0.653	0.723
K-5	36.2	0.735	0.763	0.742	0.748	0.738	0.733	0.725	0.698	0.649	0.726
Average		0.742	0.754	0.747	0.743	0.736	0.728	0.721	0.692	0.643	0.723
L-1	7.1	0.739	0.761	0.751	0.746	0.736	0.727	0.722	0.685	0.642	0.723
L-2	16.3	0.743	0.761	0.747	0.742	0.737	0.727	0.717	0.696	0.653	0.725
L-3	28.9	0.708	0.737	0.748	0.755	0.745	0.730	0.725	0.700	0.652	0.722
L-4	32.3	0.699	0.738	0.750	0.752	0.742	0.737	0.727	0.702	0.653	0.722
L-5	43.3	0.707	0.741	0.758	0.759	0.755	0.746	0.729	0.700	0.663	0.729
Average		0.719	0.748	0.751	0.751	0.743	0.733	0.724	0.696	0.652	0.724

crease in cement content. For ordinary mixtures, increasing the quantity of cement 1 per cent increases the strength about 1 per cent. It will be noted that a unit volume of very wet concrete of a given mix contains considerably less cement than mixes of normal consistency.

In the foregoing discussion it should be understood that 1 per cent increase in cement refers to the actual change in cement content. If we assume that 1:5 mix contains 20 per cent of cement (by volume of fin-

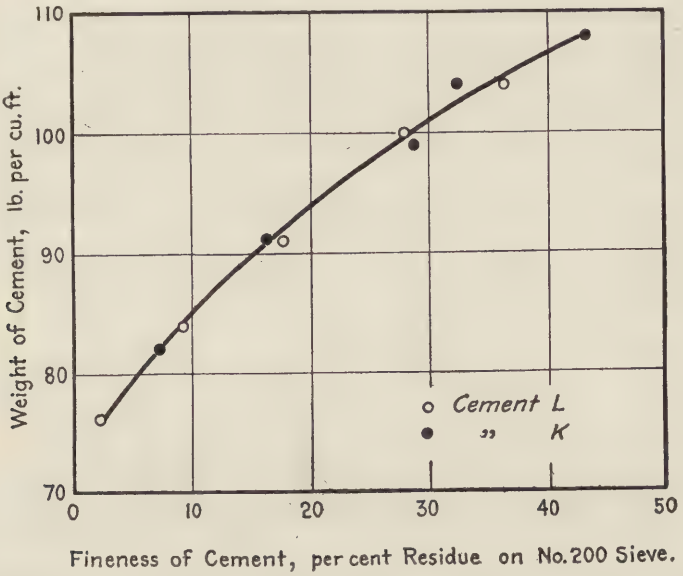


FIG. 20—EFFECT OF FINENESS ON UNIT WEIGHT OF CEMENT—SERIES 118.

Values are based on 5 to 18 tests for fineness and 2 tests for unit weights.

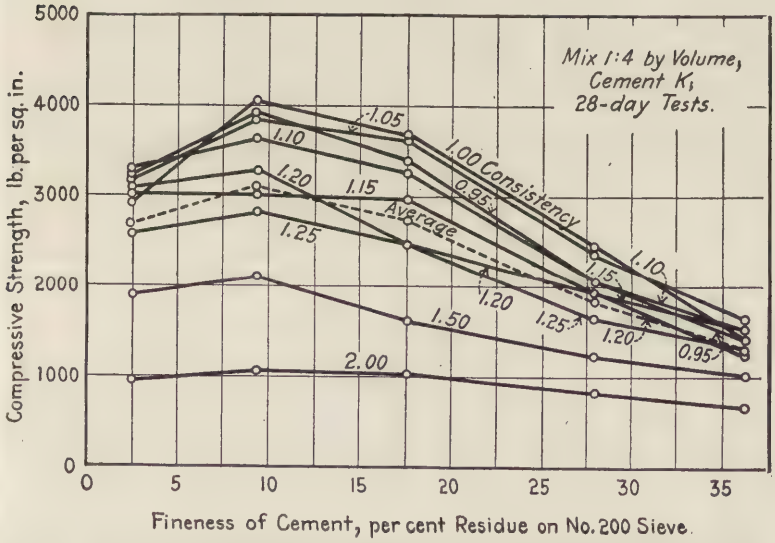


FIG. 21—EFFECT OF FINENESS OF CEMENT ON THE STRENGTH OF CONCRETE—SERIES 118.

Compression tests of 6 by 12-in. cylinders. Cement K. See Table 18.

Aggregate; sand and pebbles from Elgin, Ill., graded 0–¾ in.

ished concrete), then an increase of 1 per cent would give a cement content of 20.2 per cent (not 21 per cent as frequently stated).

Size and Grading of Aggregate.—Aggregates of different sizes and grading were used in Series 60 and 120. The effects of fineness of cement with aggregates of different gradings is shown in Fig. 19 and 34. The tests show an increase in strength with the fineness modulus of the aggre-

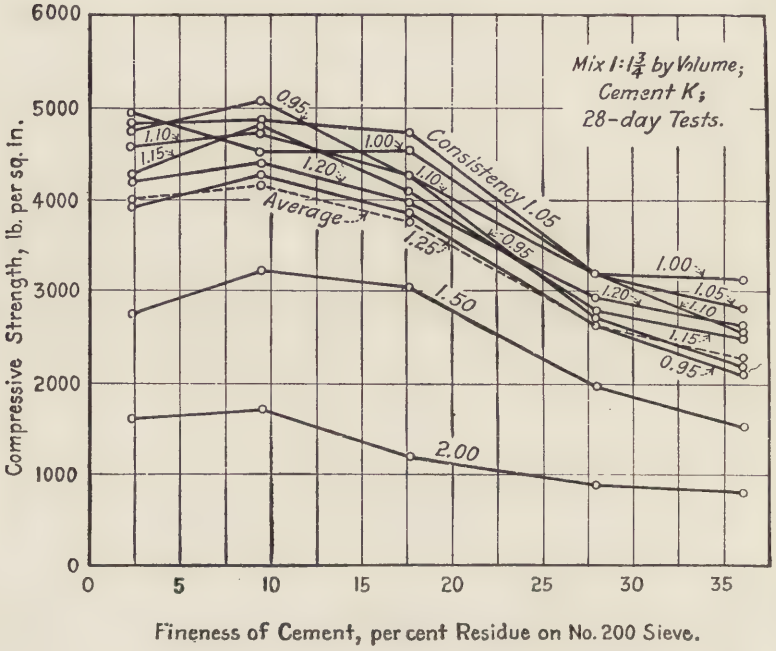


FIG. 22—EFFECT OF FINENESS OF CEMENT ON THE STRENGTH OF CONCRETE—SERIES 118.

Compression tests of 6 by 12-in. cylinders. Cement K. See Table 18.

Aggregate; celite, Elgin sand, and blast-furnace slag, graded 0–⅜ in.

gate similar to that observed in other tests made in this Laboratory. The reason for this relation is found in the fact that the water content for a given plastic condition of the concrete is dependent on the size and grading of the aggregate as measured by the fineness modulus. The finer aggregate shows a somewhat greater increase in strength with fineness of cement than the coarser gradings. (See Table 29.)

Age of Concrete.—Tests were made in Series 20, 31, 60 and 120 at ages varying from 7 days to 1 year. The results of these tests are given

in Tables 10, 14, 24, and 26. Fig. 15 gives typical age-strength curves. It will be noted that the strength of the concrete increases with age for both of the mixtures used and for all finenesses of cement.[1] Similar curves may be platted from the data in Series 20 and 120. Curves for concrete of different ages are shown in many of the diagrams.

The effect of age on the change of strength of concrete with the fineness of cement is shown in Fig. 7 and 11, and in Tables 20, 28 and 29. It is seen that the rate of change of strength decreases rapidly with the age of the concrete. A study of all of the data shows that for usual

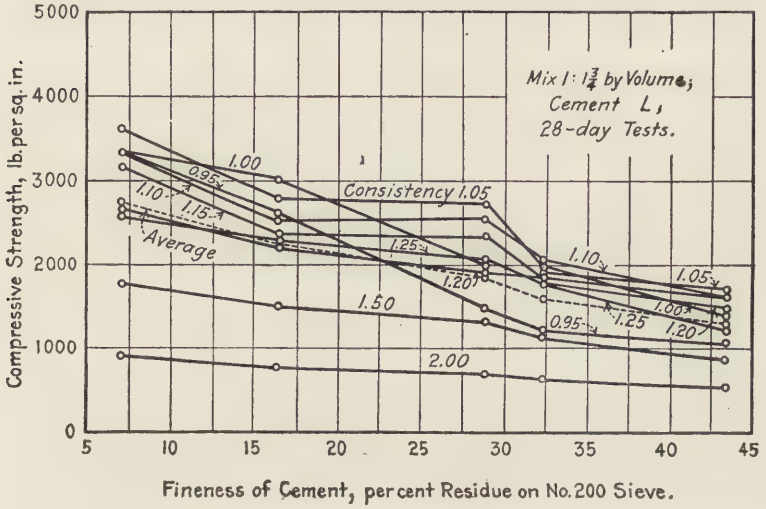


FIG. 23—EFFECT OF FINENESS OF CEMENT ON THE STRENGTH OF CONCRETE—SERIES 118.

Compression tests of 6 by 12-in. cylinders. Cement L. See Table 18.

Aggregate; celite, Elgin sand, and blast-furnace slag, graded 0–⅜ in.

mixtures tested at 28 days the increase in strength of the concrete is about 2 per cent for each 1 per cent reduction in residue on the No. 200 sieve. At 7 days, 3 months and 1 year the corresponding values are about 2.5, 1.7 and 1.4 per cent. These tests do not bear out the common belief that the strength of the concrete depends only on the "flour" content of the cement, but indicates that fine grinding merely hastens the action of the cement.

Air Analyzer Tests.—The size and grading of the particles in two lots of cement was studied by means of the air analyzer, shown in Fig. 3. This

[1] See D. A. Abrams, "Effect of Age on the Strength of Concrete," *Proceedings*, Am. Soc. Testing Mat., Vol. XVIII, Part II, p. 317 (1918).

apparatus in combination with the usual sieves enables us to determine the "sieve analysis" of cements in the same manner as for aggregates. The separation sizes were determined by microscopical measurements on a large number of the last particles carried over by the air current or

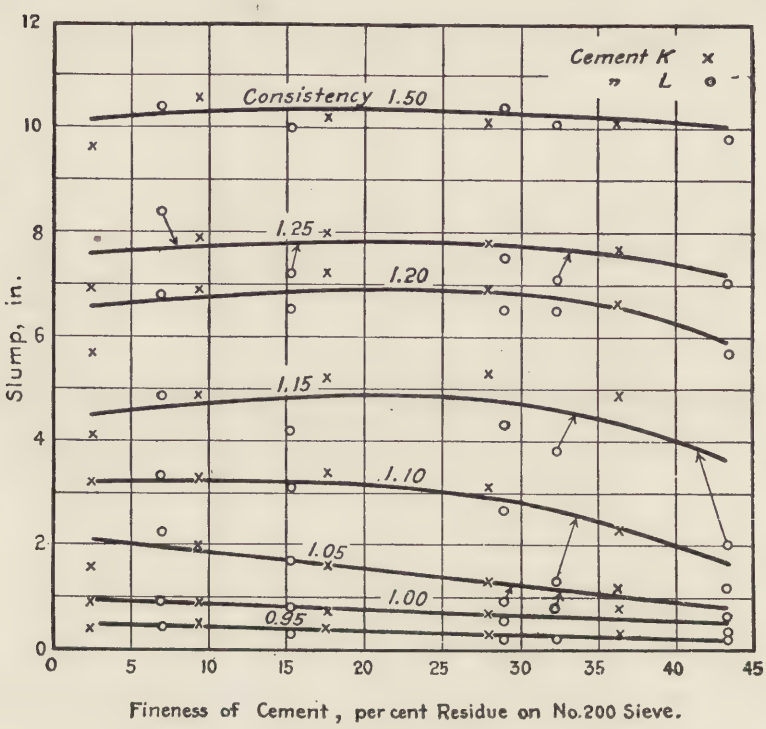


FIG. 24—EFFECT OF FINENESS OF CEMENT ON THE WORKABILITY OF CONCRETE—SERIES 118.

Tests on 6 by 12-in. cylinders. Cements K and L. See Table 21.
Mix 1:1¾ by volume.
Aggregate; celite, Elgin sand, and blast-furnace slag, graded 0–⅜ in.
Apparatus for "slump" tests shown in Fig. 1.
Each value is the average of 5 tests made on different days.

passing the sieve. The separations given in Table 5 for Cements K and L show that all the samples give smooth sieve analysis curves of the same type. If these curves are platted it will be seen that the maximum differences in the ordinates (percentages coarser than each size) comes at the No. 200 sieve. We may expect, therefore, that the residue on the No. 200 sieve is a satisfactory measure of fineness of cement.

TABLE 23—EFFECT OF FINENESS OF CEMENT ON THE STRENGTH OF CONCRETE—SERIES 120.

Compression tests of 6 by 12-in. cylinders. Mix by volume.

Aggregate, sand and pebbles from Elgin, Ill., graded 0-1½. Age at test, 28 days.

Specimens stored in damp sand; tested damp. Each value is the average of 5 tests made on different days.

Weight of all cements assumed as 94 lb. per cu. ft. in proportioning.

Mix by Volume.	Compressive Strength for Different Relative Consistencies, lb. per sq. in.													
	0.90	1.00	1.10	1.25	1.50	2.00	Average.	0.90	1.00	1.10	1.25	1.50	2.00	Average.
	CEMENT K-1—(2.4).[1]							CEMENT L-1—(7.1).[1]						
1:10	1320	1380	1220	930	640	390	980	910	820	870	610	480	310	670
1:7	2690	2540	2150	1520	900	630	1740	1770	1640	1310	950	650	450	1130
1:5	3830	3200	2900	2200	1380	720	2370	2970	2780	2060	1380	910	690	1800
1:4	3670	3690	3100	2630	1670	920	2610	2910	3850	2290	1380	1090	650	2030
1:3	4140	4170	3700	3000	2220	1020	3040	4750	3590	3380	2330	1360	740	2690
1:2	4600	4440	4260	3800	2880	1610	3600	5140	5020	4060	3560	2510	1080	3560
Average	3380	3240	2890	2350	1620	880	2380	3080	2950	2330	1700	1170	650	1980
	CEMENT K-2—(9.4).[1]							CEMENT L-2—(16.3).[1]						
1:10	1410	1420	1190	1130	800	560	1080	540	530	560	510	360	230	460
1:7	2090	2450	2370	1630	1050	750	1720	930	1080	1040	730	570	380	790
1:5	3550	3920	3260	2440	1490	860	2590	1420	1710	1580	1110	850	550	1200
1:4	3790	4340	3620	2820	2030	1060	2940	1800	2130	1740	1330	940	630	1430
1:3	4770	5370	4680	3990	2530	1140	3750	2330	2450	2030	1950	1220	630	1770
1:2	4270	5270	5300	4360	3540	1540	4050	2290	3780	3040	2660	1880	800	2410
Average	3310	3800	3400	2730	1910	980	2690	1550	1950	1660	1380	970	540	1350
	CEMENT K-3—(17.7).[1]							CEMENT L-3—(28.9).[1]						
1:10	1140	930	1060	880	620	440	840	470	740	460	440	350	200	450
1:7	1760	1680	1630	1210	930	640	1310	980	930	820	710	500	350	720
1:5	2330	2990	2700	2070	1280	920	2050	1280	1540	1440	1010	610	480	1060
1:4	3350	3550	3290	2550	1510	890	2520	1570	1900	1580	1240	740	530	1260
1:3	4050	4190	3380	2970	2060	1150	2970	1740	2050	1750	1520	990	500	1420
1:2	4030	4900	4430	3530	2640	1330	3480	1670	3060	2580	2080	1300	800	1920
Average	2780	3040	2750	2200	1510	900	2200	1280	1700	1440	1170	750	480	1140
	CEMENT K-4—(27.9).[1]							CEMENT L-4—(32.3).[1]						
1:10	750	620	710	580	500	330	580	340	390	340	350	320	250	330
1:7	1170	1250	1190	970	710	520	970	460	610	490	560	550	280	490
1:5	1850	2090	2000	1490	1050	630	1520	1000	1040	1080	800	610	400	820
1:4	2440	2590	2450	1780	1140	720	1850	740	1750	1390	1200	810	450	1060
1:3	3240	3420	3050	2530	1350	860	2410	990	2030	1910	1350	830	530	1270
1:2	3000	3800	3900	3260	1690	950	2770	1660	2730	2270	1730	1300	930	1770
Average	2080	2300	2220	1770	1070	670	1680	860	1420	1250	1000	740	470	960
	CEMENT K-5—(36.2).[1]							CEMENT L-5—(43.3).[1]						
1:10	530	490	530	440	440	300	460	390	290	290	340	230	150	280
1:7	910	860	870	940	550	470	770	440	360	470	400	370	200	370
1:5	1480	1480	1340	1020	850	730	1150	840	920	730	760	500	400	690
1:4	1390	1950	1830	1350	980	600	1350	900	1010	1030	920	750	560	860
1:3	2330	2730	2340	1730	1060	730	1820	1120	1460	1480	1100	830	730	1120
1:2	2860	3580	3160	2520	1590	880	2430	920	1840	1640	1400	730	730	1210
Average	1580	1850	1680	1330	910	620	1330	770	980	940	820	570	460	760

[1] Fineness of cement, residue on No. 200 sieve.

TABLE 24—EFFECT OF FINENESS OF CEMENT ON THE STRENGTH OF CONCRETE—SERIES 120.

(A STUDY OF CONSISTENCY.)

Compression tests of 6 by 12-in. cylinders.
Weight of all cements assumed as 94 lb. per cu. ft. in proportioning.
Aggregate, sand and pebbles from Elgin, Ill., graded 0-1½ in.
Specimens stored in damp sand; tested damp.
Each value is the average of 5 tests made on different days.

Cement.		Compressive Strength for Different Relative Consistencies lb. per sq. in.						
Ref. No.	Fineness Residue on No. 200 Sieve	0.90	1.00	1.10	1.25	1.50	2.00	Average.
1-4 MIX; 7-DAY TESTS.								
K-1	2.4	2410	2370	2080	1560	1010	450	1650
K-2	9.4	2840	2650	2320	1890	940	470	1840
K-3	17.7	2170	2000	1640	1220	690	420	1360
K-4	27.9	1490	1350	1180	810	480	300	940
K-5	36.2	1050	1010	890	610	360	260	700
Average		1990	1880	1620	1220	700	380	1300
1-4 MIX; 28-DAY TESTS.[1]								
K-1	2.4	3670	3690	3100	2630	1670	920	2610
K-2	9.4	3790	4340	3620	2820	2030	1060	2940
K-3	17.7	3350	3550	3290	2550	1510	890	2520
K-4	27.9	2440	2590	2450	1780	1140	720	1850
K-5	36.2	1390	1950	1830	1350	980	600	1350
Average		2930	3220	2860	2230	1470	840	2250
1-4 MIX; 3-MONTH TESTS.								
K-1	2.4	4180	4060	3100	2790	2090	1170	2900
K-2	9.4	4190	4820	4580	3640	2420	1290	3490
K-3	17.7	4020	4480	3920	3430	1930	1240	3170
K-4	27.9	3330	3460	2980	2190	1300	920	2360
K-5	36.2	2650	2930	2450	1970	1230	890	2020
Average		3670	3950	3410	2800	1790	1100	2790
1-4 MIX; 1-YEAR TESTS.								
K-1	2.4	5820	5090	4790	3750	2710	1610	3960
K-2	9.6	6560	6630	6030	4970	2930	1820	4820
K-3	17.7	5390	5530	5530	4660	3000	1700	4300
K-4	27.9	4670	4890	4500	3120	2170	1320	3440
K-5	36.2	3430	3830	4010	2960	1970	1310	2920
Average		5170	5190	4970	3890	2560	1550	3870

The 28-day tests in this table are the same as the 1:4 tests in Table 23.

TABLE 25—QUANTITY OF MIXING WATER IN CONCRETE—SERIES 120.

Strength tests given in Tables 23 and 24.

Water reported on basis of true volume of cement, that is, the differences in unit weights of the cements are taken in account.

Mix by Volume.	Ratio of Water to Volume of Cement for Different Relative Consistencies.											
	0.90	1.00	1.10	1.25	1.50	2.00	0.90	1.00	1.10	1.25	1.50	2.00
	CEMENT K-1—(2.4).[1]						CEMENT L-1—(7.1).[1]					
1:10	1.00	1.11	1.23	1.40	1.67	2.23	1.07	1.19	1.31	1.49	1.78	2.38
1:7	0.79	0.88	0.96	1.10	1.32	1.76	0.83	0.93	1.02	1.16	1.39	1.85
1:5	0.64	0.71	0.78	0.89	1.06	1.42	0.67	0.75	0.82	0.93	1.12	1.49
1:4	0.57	0.63	0.69	0.79	0.94	1.26	0.59	0.66	0.73	0.83	0.99	1.32
1:3	0.49	0.55	0.60	0.68	0.82	1.09	0.52	0.57	0.63	0.72	0.86	1.15
1:2	0.42	0.47	0.51	0.58	0.70	0.94	0.44	0.49	0.54	0.61	0.74	0.98
	CEMENT K-2—(9.4).[1]						CEMENT L-2—(16.3).[1]					
1:10	1.09	1.22	1.34	1.51	1.83	2.43	1.18	1.30	1.43	1.63	1.95	2.60
1:7	0.86	0.95	1.05	1.19	1.42	1.90	0.92	1.02	1.12	1.27	1.53	2.04
1:5	0.69	0.76	0.84	0.96	1.15	1.53	0.74	0.82	0.90	1.02	1.22	1.63
1:4	0.61	0.68	0.75	0.84	1.01	1.36	0.65	0.72	0.79	0.90	1.08	1.45
1:3	0.53	0.59	0.65	0.73	0.88	1.18	0.56	0.62	0.69	0.78	0.94	1.25
1:2	0.45	0.50	0.55	0.62	0.75	0.99	0.48	0.53	0.58	0.66	0.80	1.06
	CEMENT K-3—(17.7).[1]						CEMENT L-3—(28.9).[1]					
1:10	1.18	1.30	1.43	1.63	1.95	2.60	1.27	1.40	1.54	1.75	2.11	2.80
1:7	0.92	1.02	1.12	1.28	1.53	2.04	0.98	1.09	1.20	1.36	1.63	2.18
1:5	0.74	0.82	0.90	1.02	1.22	1.64	0.78	0.87	0.96	1.09	1.31	1.75
1:4	0.65	0.72	0.80	0.90	1.09	1.45	0.69	0.77	0.85	0.96	1.15	1.54
1:3	0.56	0.63	0.69	0.78	0.94	1.26	0.60	0.66	0.73	0.83	0.99	1.33
1:2	0.48	0.53	0.58	0.66	0.80	1.06	0.50	0.56	0.61	0.70	0.84	1.12
	CEMENT K-4—(27.9).[1]						CEMENT L-4—(32.3).[1]					
1:10	1.28	1.42	1.56	1.78	2.14	2.85	1.31	1.46	1.61	1.82	2.20	2.92
1:7	1.00	1.11	1.22	1.39	1.67	2.23	1.05	1.14	1.25	1.43	1.70	2.28
1:5	0.80	0.89	0.98	1.11	1.34	1.78	0.82	0.91	1.00	1.13	1.36	1.82
1:4	0.71	0.79	0.86	0.98	1.18	1.58	0.72	0.80	0.88	1.00	1.20	1.60
1:3	0.61	0.68	0.75	0.85	1.02	1.36	0.62	0.69	0.76	0.86	1.04	1.38
1:2	0.52	0.58	0.63	0.72	0.86	1.15	0.52	0.58	0.64	0.73	0.87	1.16
	CEMENT K-5—(36.2).[1]						CEMENT L-5—(43.3).[1]					
1:10	1.34	1.49	1.64	1.86	2.23	2.98	1.34	1.49	1.64	1.87	2.24	2.99
1:7	1.04	1.15	1.26	1.44	1.72	2.30	1.04	1.15	1.27	1.44	1.74	2.31
1:5	0.83	0.92	1.02	1.15	1.38	1.83	0.82	0.92	1.01	1.14	1.37	1.83
1:4	0.73	0.82	0.90	1.02	1.23	1.63	0.73	0.80	0.88	1.01	1.20	1.61
1:3	0.64	0.71	0.78	0.88	1.06	1.41	0.62	0.69	0.76	0.86	1.04	1.38
1:2	0.54	0.59	0.65	0.74	0.89	1.19	0.52	0.58	0.63	0.72	0.86	1.15

[1] Fineness of cement, residue on No. 200 sieve.

TABLE 26—EFFECT OF FINENESS OF CEMENT ON THE STRENGTH OF CONCRETE—SERIES 120.

(A STUDY OF SIZE OF AGGREGATE.)

Compression tests of 6 by 12-in. cylinders.
Consistency 1.10.
Weight of all cements assumed as 94 lb. per cu. ft. in proportioning.
Aggregate, sand and pebbles from Elgin, Ill.
Specimens stored in damp sand; tested damp.
Each value is the average of 5 tests.

Cement.		Compressive Strength for Aggregates of Different Sizes, lb. per sq. in.							
Ref. No.	Fineness Residue on No. 200 Sieve.	0-No. 28	0-No. 14	0-No. 8	0-No. 4	0-⅜ in.	0-¾ in.	0-1½ in.	Average
1-4 MIX; 7-DAY TESTS.									
K-1	2.4	410	590	730	980	1260	1940	2080	1140
K-2	9.4	390	580	790	1020	1500	1920	2320	1220
K-3	17.7	320	410	560	680	1170	1700	1640	930
K-4	27.9	210	310	390	440	700	1040	1180	610
K-5	36.2	140	200	260	380	470	780	890	450
Average		290	420	550	700	1020	1480	1620	870
1-4 MIX; 28-DAY TESTS.									
K-1	2.4	680	940	1200	1340	2350	2630	3100	1750
K-2	9.4	630	960	1260	1650	2580	2860	3620	1940
K-3	17.7	470	750	1010	1260	1760	2830	3290	1620
K-4	27.9	360	560	670	880	1290	1790	2450	1140
K-5	36.2	220	440	500	680	1080	1420	1830	880
Average		470	730	930	1160	1810	2310	2860	1470
1-4 MIX; 3-MONTH TESTS.									
K-1	2.4	940	1500	1890	2050	2760	3450	3100	2240
K-2	9.4	940	1390	1860	2280	3590	3970	4580	2660
K-3	17.7	630	1150	1430	1930	2860	3990	3920	2270
K-4	27.9	570	890	1150	1410	2160	2830	2980	1710
K-5	36.2	410	650	870	980	1740	2280	2450	1340
Average		700	1120	1440	1730	2620	3300	3410	2040
1-4 MIX; 1-YEAR TESTS.									
K-1	2.4	1520	1910	2410	3050	3560	4280	4790	3070
K-2	9.4	1220	1970	2730	3290	4760	5030	6030	3580
K-3	17.7	1240	1910	2250	2930	4320	5000	5530	3310
K-4	27.9	940	1290	1680	2230	3200	4020	4500	2550
K-5	36.2	710	1430	1310	1620	2480	3690	4010	2180
Average		1130	1700	2080	2620	3660	4400	4970	2940

TABLE 27—QUANTITY OF MIXING WATER IN CONCRETE—SERIES 120.

Strength tests given in Table 26.

Water reported on basis of true volume of cement, that is, the differences in unit weights of the cements are taken in account.

Relative consistency 1.10.

Mix 1:4 by volume.

Cement.		Ratio of Water to Volume of Cement for Aggregates of Different Size.						
Ref. No.	Fineness Residue on No. 200 Sieve.	0-No. 28	0-No. 14	0-No. 8	0-No. 4	0-⅜ in.	0-¾ in.	0-1½ in.
K-1.....	2.4	1.18	1.06	1.01	0.94	0.83	0.75	0.69
K-2.....	9.4	1.28	1.15	1.09	1.02	0.90	0.80	0.75
K-3.....	17.7	1.38	1.23	1.17	1.09	0.96	0.86	0.80
K-4.....	27.9	1.50	1.34	1.28	1.19	1.04	0.93	0.86
K-5.....	36.2	1.56	1.39	1.32	1.23	1.09	0.97	0.90

TABLE 28—CHANGE IN STRENGTH OF CONCRETE WITH FINENESS OF CEMENT—SERIES 120.

(EFFECT OF CONSISTENCY.)

Data from compression tests of 6 by 12-in. cylinders. (For details of tests see Tables 23 and 24.)

Aggregate, sand and pebbles from Elgin, Ill.

The strength of concrete increases with the fineness of the cement; reducing the residue on the No. 200 sieve by 1 point increases the strength by the percentage shown.

Mix by Volume.	Age at Test.	Change in Strength of Concrete for Each Point Change in Fineness of Cement; Per cent of Strength for 20 per cent Residue.						
		0.90[1]	1.00	1.10	1.25	1.50	2.00	Average.
CEMENT K; 0-1½ IN. AGGREGATE.								
1:10.....	28 days	3.3	3.0	2.4	3.8	1.9	2.2	2.8
1:7.....	"	2.8	3.1	3.0	2.2	2.4	1.3	2.5
1:5.....	"	2.5	2.9	2.8	2.9	2.0	1.3	2.4
1:4.....	"	3.0	2.6	2.4	2.6	2.7	2.1	2.6
1:3.....	"	2.2	2.1	2.1	2.5	3.0	1.8	2.3
1:2.....	"	1.8	1.4	1.7	1.8	3.0	2.2	2.0
Average.....		2.6	2.5	2.4	2.6	2.5	1.8	2.4
CEMENT L; 0-1½ IN. AGGREGATE.								
1:10.....	28 days	2.0	2.9	2.1	1.5	1.4	1.0	1.8
1:7.....	"	2.2	3.1	2.5	2.0	1.2	2.2	2.2
1:5.....	"	1.8	2.0	2.3	1.3	1.3	1.0	1.6
1:4.....	"	2.4	1.9	1.7	1.1	1.4	0.8	1.5
1:3.....	"	3.0	1.5	1.2	1.8	1.3	0.8	1.6
1:2.....	"	2.2	2.0	1.7	2.0	2.4	0.5	1.8
Average.....		2.3	2.2	1.9	1.6	1.5	1.0	1.8
CEMENT K: 0-1½ IN. AGGREGATE.								
1:4.....	7 days	3.1	3.2	3.1	3.6	3.2	2.0	3.0
	28 days	3.0	2.6	2.4	2.6	2.7	2.1	2.6
	3 mo.	1.6	1.9	2.2	2.1	2.2	1.7	1.9
	1 yr.	2.1	1.9	1.6	2.0	1.9	1.8	1.9
Average.....		2.4	2.4	2.3	2.6	2.5	1.9	2.4

[1]Relative consistency of concrete.

TABLE 29—CHANGE IN STRENGTH OF CONCRETE WITH FINENESS OF CEMENT—SERIES 120.

(EFFECT OF SIZE OF AGGREGATE.)

Data from compression tests of 6 by 12-in. cylinders. (For details of tests see Table 26.)

Aggregate, sand and pebbles from Elgin, Ill.

Cement K, relative consistency 1.10.

The strength of concrete increases with the fineness of the cement; reducing the residue on the No. 200 sieve by 1 point increases the strength by the percentages shown.

Mix by Volume.	Age at Test.	Change in Strength of Concrete for Each Point Change in Fineness of Cement; Per cent of Strength for 20 per cent Residue.							
		0-No. 28[1]	0-No. 14	0-No. 8	0-No. 4	0-⅜ in.	0-¾ in.	0-1½in.	Average.
1:4.....	7 days	4.0	2.2	3.2	3.2	3.4	2.6	3.1	3.1
	28 days	3.3	2.9	2.9	2.8	2.6	2.5	2.4	2.8
	3 mos.	2.6	2.5	2.5	2.8	2.3	2.0	2.2	2.4
	1 yr.	2.2	1.6	2.5	2.5	2.4	1.3	1.5	2.0
Average.....		3.0	2.3	2.8	2.8	2.7	2.1	2.3	2.6

[1]Size of aggregate.

TABLE 30—SLUMP TESTS FOR CONSISTENCY OF CONCRETE—SERIES 120.

Tests made on 6 by 12-in. cylinders.

The slump test was made by molding a 6 by 12-in. cylinder by puddling with a ⅝-in. steel bar, then withdrawing the metal form by a steady, upward pull. The shortening of the fresh concrete is measured in inches. This is the "slump." The apparatus used for lifting the form is shown in Fig. 1.

Aggregate, sand and pebbles from Elgin, Ill.

Relative consistency 1.10.

Each value is the average of 5 tests made on different days.

Ref. No.	Fineness Residue on No. 200 Sieve.	Slump for Different Sizes of Aggregate, in.							
		0-No. 28	0-No. 14	0-No. 8	0-No. 4	0-⅜ in.	0-¾ in.	0-1½ in.	Average.
K-1.....	2.4	0.4	0.5	1.0	2.1	4.3	4.1	2.6	2.1
K-2.....	9.4	0.2	0.3	0.4	3.1	5.3	5.4	5.0	2.8
K-3.....	17.7	0.1	0.2	0.6	0.4	3.0	4.5	5.0	2.0
K-4.....	27.9	0.1	0.2	0.7	0.3	0.5	2.3	1.2	0.8
K-5.....	36.2	0.3	1.2	1.0	0.3	0.4	1.7	1.8	1.0
Average.....		0.2	0.5	0.7	1.2	2.7	3.6	3.1	1.7

TABLE 31—SLUMP TESTS FOR CONSISTENCY OF CONCRETE—SERIES 120.

Tests made on 6 by 12-in. cylinders.

The slump test was made by molding a 6 by 12-in. cylinder by puddling with a ⅝-in. steel bar, then withdrawing the metal form by a steady, upward pull. The shortening of the fresh concrete is measured in inches. This is the "slump." The apparatus used for lifting the form is shown in Fig. 1.

Aggregate, sand and pebbles from Elgin, Ill., graded 0-1½ in.

Each value for Cement K is the average of 5 tests; for Cement L the average of 3 tests.

Mix by Volume.	Slump for Different Consistencies, in.											
	0.90	1.00	1.10	1.25	1.50	2.00	0.90	1.00	1.10	1.25	1.50	2.00
	CEMENT K-1—(2.4).[1]						CEMENT L-1—(7.1).[1]					
1:10	2.9	1.4	3.0	5.0	6.8	7.5	7.4	2.6	4.1	7.4	7.6	7.4
1:7	0.2	0.4	0.4	4.7	8.1	8.6	0.1	0.1	3.0	4.2	8.7	8.0
1:5	2.8	8.5	3.8	6.7	8.8	....	2.4	0.7	2.0	5.8	8.1	....
1:4	0.3	0.9	2.6	8.3	9.1	....	0.3	5.8	4.4	7.7	8.8	....
1:3	0.6	2.8	5.9	8.3	9.3	....	0.6	3.6	7.6	8.9	9.3	....
1:2	0.2	0.8	3.8	7.9	8.4	....	0.4	1.6	7.0	9.3	10.3	....
Average	1.2	2.5	3.2	6.8	8.4	....	1.9	2.4	4.7	7.2	8.8	7.7
	CEMENT K-2—(9.4).[1]						CEMENT L-2—(16.3).[1]					
1:10	3.0	5.3	4.4	1.9	6.8	7.6	7.6	5.8	5.4	0.1	5.9	6.8
1:7	1.5	0.1	0.3	5.6	7.0	7.6	0.2	0.1	0.3	1.4	2.8	8.0
1:5	0.2	0.6	1.9	4.3	8.8	....	0.1	0.4	2.2	2.9	3.9	5.8
1:4	0.2	0.6	5.0	6.0	8.2	....	0.2	0.4	2.3	5.7	6.1	8.7
1:3	0.3	0.9	4.2	7.4	8.3	....	0.2	2.0	6.7	7.7	8.6	9.0
1:2	0.2	0.8	2.9	8.0	8.6	....	0.1	1.1	3.4	8.2	9.1	....
Average	0.9	1.4	3.1	5.5	8.0	....	1.4	1.6	3.4	4.3	6.1	7.7
	CEMENT K-3—(17.7).[1]						CEMENT L-3—(28.9).[1]					
1:10	6.9	3.1	4.3	4.2	6.6	6.3	7.1	4.6	4.4	4.5	7.0	6.2
1:7	1.4	0.2	0.4	0.4	3.1	8.0	2.3	0.2	0.4	2.7	5.2	8.1
1:5	0.1	0.4	1.3	4.1	6.9	7.3	0.1	0.3	0.9	3.9	3.1	6.3
1:4	0.2	2.0	5.0	6.0	7.6	....	0.1	0.4	1.5	6.3	4.5	7.1
1:3	0.3	2.0	5.5	7.8	9.1	....	0.2	0.6	5.0	6.9	7.9	....
1:2	0.2	1.1	4.6	8.4	8.3	....	0.1	2.9	4.3	8.7	9.0	....
Average	1.5	1.5	3.5	5.2	6.9	....	1.6	1.5	2.7	5.5	6.1	6.9
	CEMENT K-4—(27.9).[1]						CEMENT L-4—(32.3).[1]					
1:10	7.5	6.2	5.1	5.7	6.1	7.0	7.5	7.2	7.4	4.8	6.6	5.9
1:7	3.0	0.3	0.1	0.2	5.0	7.4	2.4	2.0	2.6	3.0	2.0	6.7
1:5	0.1	0.2	0.6	1.5	4.6	....	0.1	0.1	0.4	1.2	4.8	7.6
1:4	0.1	0.4	1.2	4.2	5.4	4.2	0.1	0.5	2.8	4.2	4.1	....
1:3	0.3	1.5	4.6	7.9	6.7	....	0.1	1.3	5.3	7.2	7.1	....
1:2	0.3	0.6	5.2	8.3	8.3	....	0.1	0.6	5.7	8.2	3.4	....
Average	1.9	1.5	2.8	4.6	6.0	....	1.7	2.0	4.0	4.8	4.7	6.7
	CEMENT K-5—(36.2).[1]						CEMENT L-5—(43.3).[1]					
1:10	6.8	7.4	6.8	4.3	4.5	6.4	7.7	7.7	6.7	4.0	....	....
1:7	3.6	1.5	0.2	0.3	1.6	5.1	6.7	4.5	2.7	5.3	....	....
1:5	2.4	0.2	1.8	1.1	3.3	4.8	1.7	0.1	0.2	1.3	....	....
1:4	0.1	0.3	1.8	3.4	3.9	....	2.5	0.1	1.3	4.1	....	....
1:3	0.2	0.6	4.4	7.2	5.9	....	0.1	0.3	1.2	6.7	....	....
1:2	0.1	0.8	5.3	8.3	8.3	....	0.3	0.8	6.4	8.6	9.4	....
Average	2.2	1.8	3.4	4.1	4.6	....	3.2	2.2	3.1	5.0	....	....

[1] Fineness of cement, residue on No. 200 sieve.

TABLE 32—EFFECT OF FINENESS OF CEMENT ON YIELD AND DENSITY OF CONCRETE—SERIES 120.

6 by 12-in. cylinders.
Aggregates, sand and pebbles from Elgin, Ill., graded 0-1½ in.
Yield is the volume of concrete produced by 1 volume of mixed aggregate.
Density is the total solid material in the mass.
Weights were determined immediately on removal from the forms.
Each value is the average of 5 tests made on different days.

Mix by Vol.	Yield for Different Consistencies.							Density for Different Consistencies.						
	0.90	1.00	1.10	1.25	1.50	2.00	Average.	0.90	1.00	1.10	1.25	1.50	2.00	Average
CEMENT K-1—(2.4).[1]														
1:10...	1.001	1.000	0.993	0.995	1.002	1.052	1.007	0.814	0.815	0.821	0.820	0.813	0.774	0.809
1:7...	0.995	0.993	1.007	1.024	1.039	1.079	1.023	0.840	0.842	0.831	0.815	0.804	0.773	0.817
1:5...	1.018	1.038	1.045	1.070	1.081	1.141	1.065	0.848	0.832	0.826	0.806	0.797	0.756	0.811
1:4...	1.060	1.076	1.090	1.119	1.146	1.195	1.114	0.837	0.825	0.814	0.794	0.775	0.743	0.798
1:3...	1.140	1.150	1.164	1.187	1.218	1.285	1.191	0.814	0.807	0.797	0.783	0.763	0.722	0.781
1:2...	1.294	1.289	1.309	1.335	1.377	1.467	1.345	0.779	0.783	0.770	0.756	0.733	0.688	0.751
Avg...	1.085	1.091	1.101	1.121	1.144	1.203	1.124	0.822	0.817	0.810	0.782	0.781	0.743	0.794
CEMENT K-2—(9.4).[1]														
1:10...	1.015	1.005	0.991	0.987	1.008	1.035	1.007	0.802	0.810	0.822	0.825	0.808	0.788	0.809
1:7...	1.020	1.005	0.998	1.007	1.037	1.076	1.024	0.818	0.831	0.837	0.829	0.805	0.776	0.816
1:5...	1.028	1.023	1.036	1.052	1.079	1.127	1.057	0.840	0.845	0.838	0.820	0.800	0.767	0.817
1:4...	1.068	1.061	1.075	1.088	1.120	1.175	1.098	0.830	0.836	0.825	0.816	0.792	0.755	0.809
1:3...	1.160	1.130	1.148	1.168	1.205	1.260	1.178	0.800	0.822	0.808	0.795	0.770	0.737	0.789
1:2...	1.314	1.265	1.291	1.320	1.358	1.447	1.332	0.767	0.797	0.780	0.764	0.743	0.697	0.758
Avg...	1.101	1.082	1.090	1.104	1.134	1.187	1.116	0.810	0.824	0.818	0.808	0.786	0.753	0.800
CEMENT K-3—(17.7).[1]														
1:10...	1.028	1.012	1.005	0.987	1.005	1.042	1.013	0.793	0.804	0.810	0.826	0.810	0.782	0.804
1:7...	1.027	1.011	1.011	1.014	1.030	1.061	1.026	0.813	0.826	0.826	0.823	0.810	0.787	0.814
1:5...	1.036	1.027	1.042	1.050	1.070	1.111	1.056	0.833	0.841	0.829	0.823	0.807	0.777	0.818
1:4...	1.073	1.060	1.073	1.090	1.125	1.173	1.099	0.827	0.837	0.827	0.814	0.788	0.756	0.808
1:3...	1.136	1.138	1.147	1.168	1.200	1.254	1.174	0.817	0.816	0.810	0.796	0.772	0.740	0.792
1:2...	1.305	1.275	1.282	1.308	1.338	1.425	1.322	0.772	0.790	0.785	0.771	0.753	0.707	0.763
Avg...	1.102	1.087	1.093	1.103	1.128	1.178	1.115	0.809	0.819	0.814	0.809	0.790	0.758	0.800
CEMENT K-4—(27.9).[1]														
1:10...	1.029	1.028	1.005	1.012	1.012	1.041	1.021	0.792	0.793	0.811	0.805	0.805	0.783	0.798
1:7...	1.032	1.020	1.011	1.006	1.036	1.076	1.030	0.808	0.818	0.826	0.830	0.806	0.776	0.811
1:5...	1.057	1.035	1.042	1.051	1.076	1.119	1.063	0.817	0.834	0.828	0.821	0.802	0.771	0.812
1:4...	1.088	1.072	1.081	1.091	1.127	1.173	1.105	0.817	0.826	0.820	0.812	0.787	0.756	0.803
1:3...	1.143	1.135	1.145	1.159	1.203	1.255	1.173	0.812	0.818	0.811	0.801	0.771	0.740	0.792
1:2...	1.321	1.280	1.291	1.308	1.355	1.431	1.331	0.763	0.789	0.780	0.772	0.744	0.704	0.759
Avg...	1.112	1.095	1.098	1.104	1.135	1.182	1.120	0.802	0.813	0.813	0.807	0.786	0.755	0.796
CEMENT K-5—(36.2).[1]														
1:10...	1.027	1.025	1.018	1.012	1.020	1.054	1.026	0.794	0.795	0.801	0.805	0.800	0.772	0.794
1:7...	1.040	1.031	1.018	1.021	1.035	1.074	1.036	0.803	0.810	0.822	0.819	0.807	0.777	0.806
1:5...	1.056	1.041	1.054	1.058	1.082	1.116	1.068	0.817	0.829	0.818	0.816	0.797	0.774	0.808
1:4...	1.100	1.080	1.088	1.100	1.125	1.171	1.111	0.806	0.821	0.816	0.806	0.788	0.757	0.799
1:3...	1.165	1.135	1.143	1.164	1.195	1.246	1.175	0.796	0.818	0.811	0.797	0.777	0.745	0.791
1:2...	1.310	1.270	1.300	1.315	1.351	1.429	1.329	0.770	0.793	0.775	0.766	0.745	0.705	0.759
Avg...	1.116	1.197	1.104	1.112	1.135	1.182	1.124	0.798	0.811	0.807	0.802	0.786	0.755	0.793

[1] Fineness of cement, residue on No. 200 sieve.

TABLE 33—EFFECT OF FINENESS OF CEMENT ON YIELD AND DENSITY OF CONCRETE—SERIES 120.

6 by 12-in. cylinders.
Aggregates, sand and pebbles from Elgin, Ill., graded 0-1½ in.
Yield is the volume of concrete produced by 1 volume of mixed aggregate.
Density is the total solid material in the mass.
Weights were determined immediately on removal from the forms.
Each value is the average of 5 tests made on different days.

Mix by Vol.	Yield for Different Consistencies							Density for Different Consistencies.						
	0.90	1.00	1.10	1.25	1.50	2.00	Average.	0.90	1.00	1.10	1.25	1.50	2.00	Average.
CEMENT L-1—FINENESS 7.1.														
1:10...	1.008	1.012	1.998	1.000	1.005	1.042	1.011	0.809	0.805	0.816	0.815	0.810	0.782	0.806
1:7...	1.005	0.998	1.004	1.021	1.043	1.070	1.023	0.830	0.837	0.831	0.818	0.800	0.781	0.816
1:5...	1.022	1.029	1.036	1.052	1.071	1.120	1.055	0.844	0.839	0.834	0.820	0.806	0.771	0.819
1:4...	1.073	1.073	1.073	1.101	1.134	1.175	1.105	0.826	0.826	0.826	0.806	0.781	0.755	0.803
1:3...	1.112	1.137	1.153	1.168	1.198	1.260	1.171	0.833	0.816	0.805	0.795	0.775	0.737	0.793
1:2...	1.270	1.272	1.302	1.320	1.359	1.434	1.326	0.793	0.791	0.773	0.763	0.742	0.703	0.761
Avg...	1.082	1.087	1.094	1.110	1.135	1.184	1.115	0.822	0.819	0.814	0.803	0.786	0.755	0.800
CEMENT L-2—FINENESS 16.3.														
1:10...	1.036	1.027	1.032	1.005	1.041	1.050	1.032	0.787	0.794	0.790	0.811	0.782	0.777	0.790
1:7...	1.049	1.019	1.012	1.014	1.036	1.082	1.035	0.796	0.820	0.824	0.823	0.806	0.771	0.807
1:5...	1.056	1.035	1.050	1.051	1.076	1.119	1.064	0.818	0.834	0.822	0.821	0.803	0.772	0.812
1:4...	1.088	1.073	1.080	1.091	1.125	1.180	1.106	0.816	0.826	0.821	0.813	0.788	0.752	0.803
1:3...	1.175	1.135	1.150	1.159	1.203	1.248	1.183	0.790	0.817	0.807	0.801	0.771	0.744	0.788
1:2...	1.350	1.280	1.290	1.316	1.355	1.440	1.338	0.747	0.787	0.782	0.766	0.744	0.700	0.741
Avg...	1.112	1.095	1.102	1.106	1.139	1.186	1.126	0.792	0.813	0.808	0.806	0.782	0.753	0.790
CEMENT L-3—FINENESS 28.9.														
1:10..	1.050	1.055	1.024	1.020	1.020	1.069	1.039	0.776	0.772	0.795	0.799	0.799	0.762	0.784
1:7...	1.039	1.039	1.023	1.032	1.057	1.079	1.045	0.804	0.804	0.815	0.808	0.791	0.774	0.799
1:5...	1.070	1.055	1.048	1.058	1.090	1.118	1.073	0.806	0.818	0.823	0.816	0.792	0.772	0.804
1:4...	1.100	1.085	1.085	1.098	1.124	1.171	1.110	0.806	0.818	0.818	0.808	0.789	0.757	0.799
1:3...	1.182	1.150	1.142	1.172	1.195	1.262	1.184	0.785	0.807	0.812	0.791	0.777	0.735	0.784
1:2...	1.377	1.261	1.287	1.302	1.343	1.400	1.328	0.732	0.798	0.783	0.773	0.750	0.720	0.759
Avg...	1.136	1.108	1.102	1.114	1.138	1.183	1.130	0.785	0.803	0.808	0.799	0.783	0.753	0.788
CEMENT L-4—FINENESS 32.3.														
1:10...	1.056	1.062	1.055	1.040	1.040	1.115	1.061	0.773	0.767	0.773	0.783	0.783	0.731	0.768
1:7...	1.061	1.008	1.051	1.046	1.041	1.094	1.060	0.787	0.782	0.794	0.799	0.802	0.763	0.788
1:5...	1.083	1.062	1.061	1.062	1.089	1.123	1.080	0.797	0.812	0.813	0.812	0.793	0.768	0.799
1:4...	1.139	1.085	1.079	1.089	1.123	1.160	1.112	0.779	0.817	0.822	0.815	0.790	0.765	0.798
1:3...	1.195	1.126	1.141	1.152	1.191	1.243	1.175	0.777	0.824	0.813	0.805	0.779	0.746	0.791
1:2...	1.345	1.270	1.285	1.293	1.348	1.402	1.324	0.749	0.794	0.784	0.779	0.748	0.718	0.762
Avg...	1.150	1.112	1.112	1.114	1.139	1.190	1.135	0.777	0.799	0.799	0.799	0.782	0.748	0.784
CEMENT L-5—FINENESS 43.3.														
1:10...	1.048	1.048	1.038	1.039	1.069	1.051	1.049	0.777	0.777	0.785	0.784	0.763	0.775	0.777
1:7...	1.067	1.051	1.064	1.045	1.053	1.162	1.074	0.782	0.795	0.784	0.799	0.792	0.718	0.778
1:5...	1.090	1.075	1.067	1.070	1.093	1.142	1.089	0.792	0.803	0.810	0.807	0.789	0.756	0.793
1:4...	1.138	1.112	1.091	1.100	1.120	1.157	1.119	0.780	0.797	0.813	0.806	0.792	0.767	0.792
1:3...	1.193	1.161	1.155	1.165	1.195	1.230	1.183	0.776	0.798	0.803	0.796	0.776	0.754	0.784
1:2...	1.391	1.289	1.300	1.295	1.340	1.412	1.338	0.724	0.782	0.775	0.778	0.752	0.714	0.754
Avg...	1.154	1.123	1.119	1.119	1.145	1.192	1.142	0.772	0.792	0.795	0.795	0.777	0.747	0.779

TABLE 34—EFFECT OF FINENESS OF CEMENT ON YIELD AND DENSITY OF CONCRETE—SERIES 120.

6 by 12-in. cylinders.
Aggregates, sand and pebbles from Elgin, Ill.
Yield is the volume of concrete produced by 1 volume of mixed aggregate.
Density is the total solid material in the mass.
Weights were determined immediately on removal from the forms.
Relative consistency 1.10.
Each value is the average of 20 tests made on 5 days.

Cement Ref. No.	0–No. 28	0–No. 14	0–No. 8	0–No. 4	0–⅜ in.	0–¾ in.	0–1½ in.	Average.
YIELD FOR DIFFERENT SIZES OF AGGREGATE.								
K-1	1.210	1.170	1.150	1.151	1.109	1.108	1.090	1.141
K-2	1.196	1.150	1.130	1.140	1.099	1.090	1.075	1.126
K-3	1.215	1.148	1.129	1.139	1.082	1.089	1.073	1.125
K-4	1.245	1.175	1.146	1.148	1.098	1.097	1.081	1.141
K-5	1.267	1.180	1.162	1.155	1.103	1.095	1.088	1.150
Average	1.227	1.165	1.143	1.147	1.098	1.096	1.081	1.137
DENSITY FOR DIFFERENT SIZES OF AGGREGATE.								
K-1	0.621	0.653	0.674	0.704	0.754	0.791	0.814	0.716
K-2	0.628	0.664	0.686	0.711	0.760	0.804	0.825	0.726
K-3	0.618	0.665	0.687	0.712	0.771	0.805	0.827	0.726
K-4	0.603	0.649	0.677	0.706	0.761	0.799	0.820	0.716
K-5	0.592	0.646	0.666	0.702	0.757	0.800	0.816	0.711
Average	0.612	0.655	0.678	0.707	0.760	0.800	0.820	0.719

TABLE 35—ELONGATION AND CONTRACTION OF CONCRETE—SERIES 120.

Based on length measurements of 180 6 by 12-in. cylinders.
Time intervals refer to the preceding *change* in storage condition.
Plus means an increase in length.
A change in length of 0.001 in. in a 6 by 12-in. cylinder is equivalent to 0.0083 per cent.

Cement.		Mix by Volume.	Relative Consistency.	Change in Length of Cylinder, in.								
Ref. No.	Fineness, Residue on No. 200 Sieve.			28 d. in dampSand.	7 d. in. Air.	21 d. in Air.	28 d. in Air.	42 d. in Air.	7 d. in Water.	28 d. in Water.	28 d. in Air.	Total Regardless of Sign.
EFFECT OF FINENESS OF CEMENT.												
K-1	2.4	Values for each fineness are average of all mixes and consistencies (36 cylinders).		−0.002	0.000	−0.003	−0.004	−0.006	+0.003	+0.004	−0.002	0.024
K-2	9.4			+0.002	−0.001	−0.004	−0.005	−0.007	+0.003	+0.004	−0.002	0.028
K-3	17.7			+0.001	0.000	−0.003	−0.005	−0.007	+0.004	+0.004	−0.002	0.026
K-4	27.9			+0.003	−0.004	−0.005	−0.006	−0.006	+0.004	+0.003	−0.001	0.032
K-5	36.9			+0.001	−0.004	−0.004	−0.006	−0.007	+0.004	+0.001	−0.001	0.028
			Grand average[1]	+0.001	−0.002	−0.004	−0.005	−0.007	+0.004	+0.003	−0.002	
EFFECT OF QUANTITY OF CEMENT.												
Values for each mix are average of all finenesses and consistencies (30 cylinders).		1:10	....	+0.003	−0.003	−0.004	−0.005	−0.007	+0.003	+0.003	−0.002	0.030
		1:7	....	0.000	−0.002	−0.004	−0.005	−0.007	+0.005	+0.004	−0.002	0.029
		1:5	....	0.000	−0.003	−0.004	−0.006	−0.007	+0.003	+0.003	−0.001	0.027
		1:4	....	−0.001	−0.001	−0.004	−0.005	−0.006	+0.004	+0.004	−0.001	0.026
		1:3	....	0.000	−0.001	−0.003	−0.005	−0.006	+0.004	+0.003	−0.002	0.024
		1:2	....	+0.002	−0.002	−0.005	−0.006	−0.007	+0.003	+0.003	−0.001	0.029
			Grand average[1]	+0.001	−0.002	−0.004	−0.005	−0.007	+0.004	+0.003	−0.002	
EFFECT OF CONSISTENCY OF CONCRETE.												
Values for each consistency are average of all finenesses and mixes (30 cylinders).		....	0.90	0.000	−0.002	−0.004	−0.005	−0.007	+0.003	+0.004	−0.002	0.027
		....	1.00	0.000	−0.002	−0.005	−0.005	−0.007	+0.004	+0.004	−0.002	0.029
		....	1.10	0.000	−0.001	−0.003	−0.004	−0.006	+0.004	+0.004	−0.002	0.024
		....	1.25	+0.002	−0.002	−0.004	−0.004	−0.006	+0.004	+0.003	−0.001	0.026
		....	1.50	+0.002	−0.002	−0.004	−0.005	−0.006	+0.004	+0.003	−0.001	0.027
		....	2.00	+0.001	−0.001	−0.004	−0.005	−0.007	+0.003	+0.003	−0.001	0.025
			Grand average[1]	+0.001	−0.002	−0.004	−0.005	−0.007	+0.004	+0.003	−0.002	.....

[1] Grand average values are based on measurements on all cylinders.

Further studies of the cements by means of the air analyzer are under way. It is too early to attempt a complete discussion of the function of particles of various sizes in cement.

Mortar Tests.—Mortar tests were made on all the cements used. Little consideration has been given to these tests in the foregoing discussion; however, the tables give the complete results. The compression tests of mortar in general confirm the results of the concrete tests. The

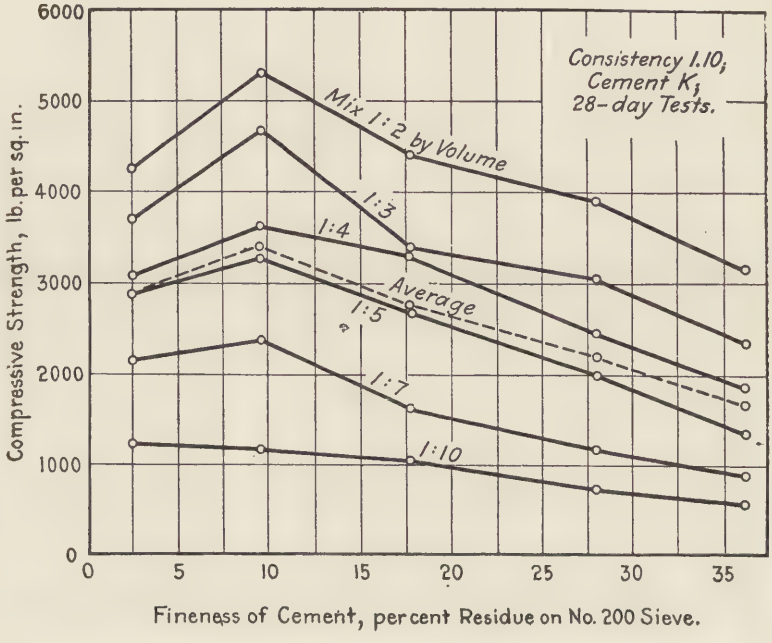


FIG. 25—EFFECT OF FINENESS OF CEMENT ON THE STRENGTH OF CONCRETE—SERIES 120.

Compression tests of 6 by 12-in. cylinders. See Table 23.
Cement K. Relative consistency 1.10.
Similar diagrams may be drawn for other consistences.

briquette tests were erratic and cannot be interpreted as showing the same relation as found in the concrete investigations. Increase in strength of mortar with the fineness of the cement is shown in Fig. 5, 6 and 10.

Elongation and Contraction of Concrete.—Tests on the elongation and contraction, due to storage conditions, were made on 180 6 by 12-in. concrete cylinders in Series 120, by means of the apparatus shown in Fig. 4. The tests included cements of 5 different finenesses, 6 different mixtures,

and 6 different consistencies. Specimens were first stored in damp sand, followed by periods of air and water storage. The results of the tests are given in Table 35. Concrete of all mixes and consistencies showed expansion in damp sand and water storage and contraction in air. The change in length is practically independent of the fineness of cement and is influenced only slightly by the mix. The richer mixtures show somewhat less change in length than the leaner ones. The consistency of the concrete had little or no influence on the expansion or contraction.

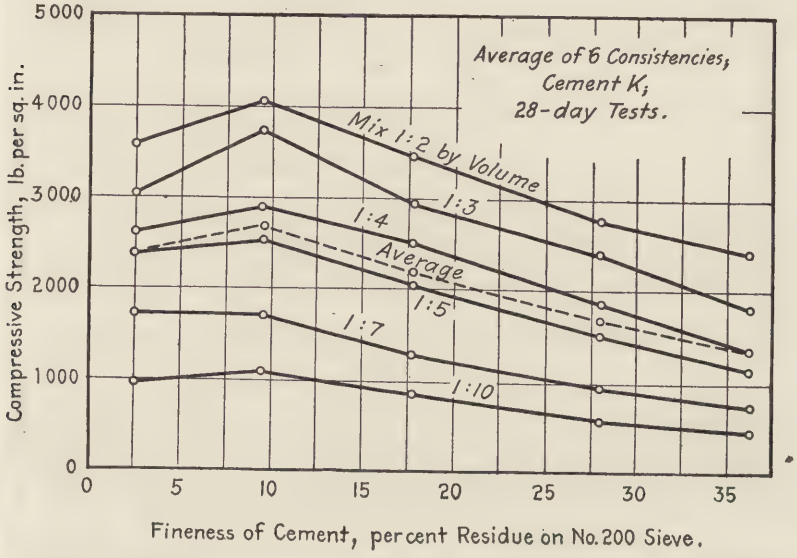


FIG. 26—EFFECT OF FINENESS OF CEMENT ON THE STRENGTH OF CONCRETE—SERIES 120.

Compression tests of 6 by 12-in. cylinders. See Table 23.
Cement K. Average of 6 consistencies. Compare Fig. 29.

Yield and Density of Concrete.—Yield and density of concrete were calculated for tests in Series 118 and 120; see Tables 22, 32 to 34. The yield is computed on the basis of the original volume of the mixed aggregate, the unit weights of aggregate being determined by the method described above. The yield is not appreciably affected by the fineness of the cement. It is clearly influenced by both consistency of the concrete and the mix. For usual mixtures and consistencies this method gives yields only a little higher than the volumes of the aggregate. For 1:5 mix of aggregates graded to 1½ in. (Tables 32 and 33) we find a yield of about 1.05. For similar very wet mixtures the yield is increased to about 1.12.

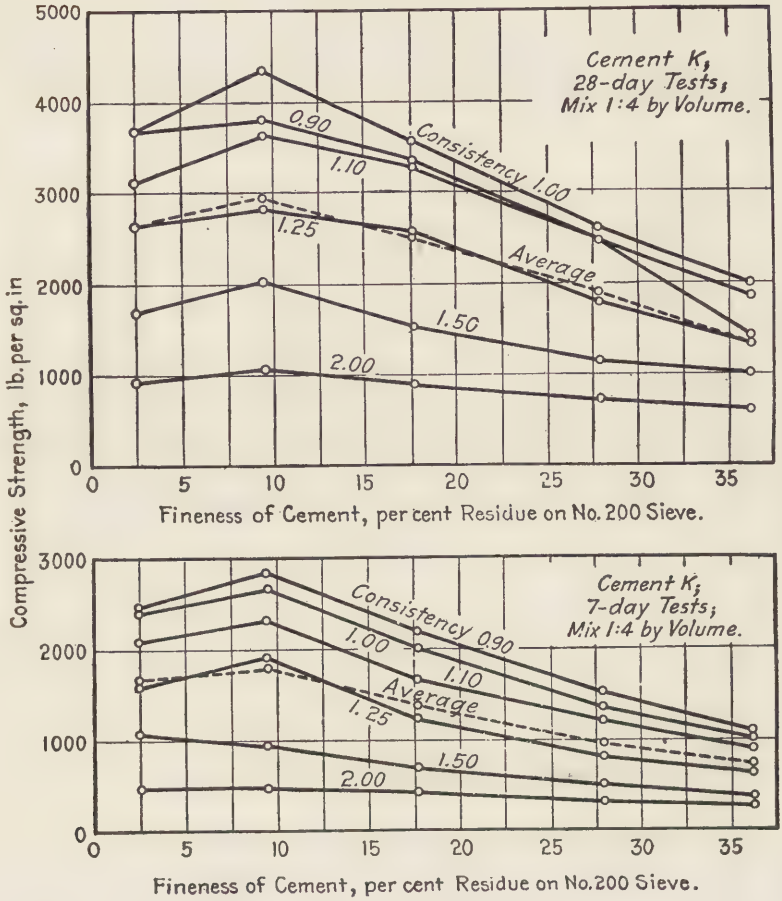


FIG. 27—EFFECT OF FINENESS OF CEMENT ON THE STRENGTH OF CONCRETE—SERIES 120.

Compression tests of 6 by 12-in cylinders. See Table 24.
Cement K. Age at test 7 and 28 days.
The 28-day curve for the 1.10 consistency is the same as the 1:4 mix in Fig. 25.
Similar curves may be drawn for the 3-month tests.

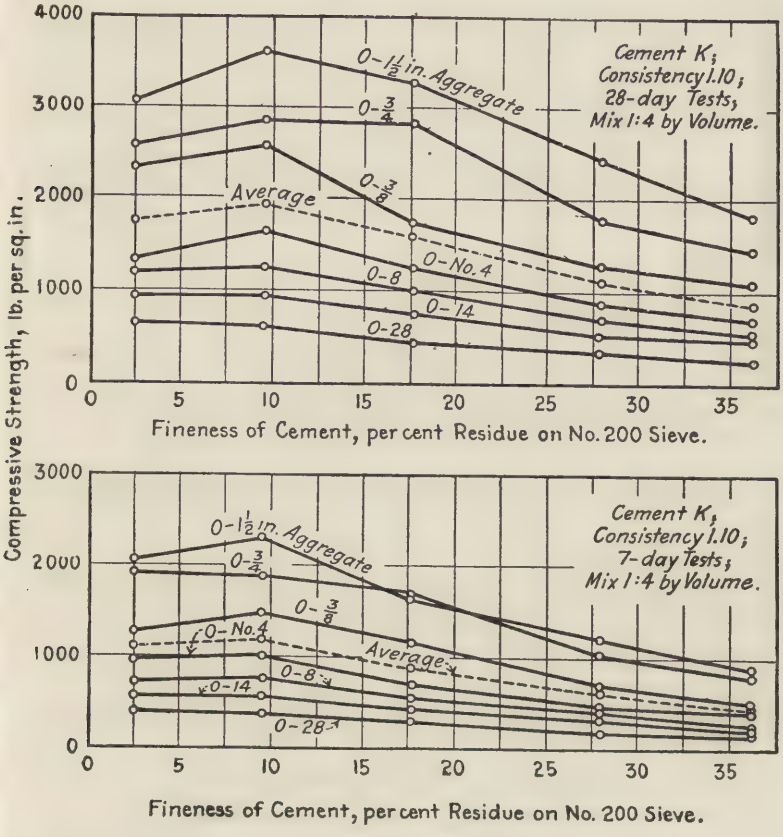


FIG. 28—EFFECT OF FINENESS OF CEMENT ON THE STRENGTH OF CONCRETE—SERIES 120.

Compression tests of 6 by 12-in. cylinders. See Table 26.
Cement K. Age at test 7 and 28 days.
The curves for the 0–1½-in. aggregate are the same as for 1.10 consistency in Fig. 27.

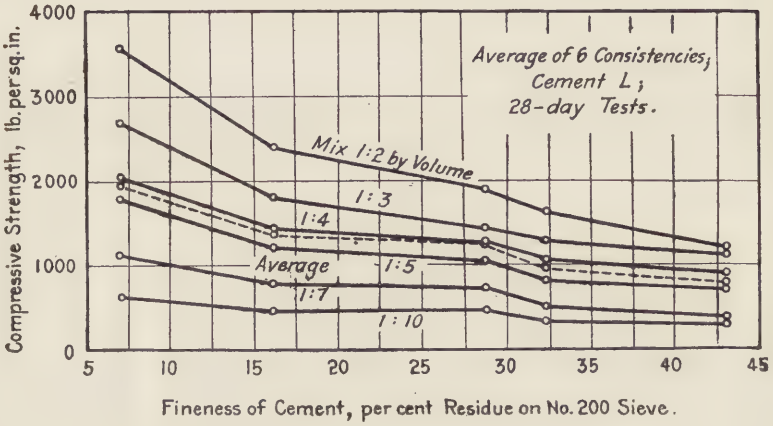


FIG. 29—EFFECT OF FINENESS OF CEMENT ON THE STRENGTH OF CONCRETE—SERIES 120.

Compression tests of 6 by 12-in. cylinders. See Table 23.
Cement L. Average of 6 consistencies. Compare Fig. 26.
Similar diagrams may be platted for other consistencies.

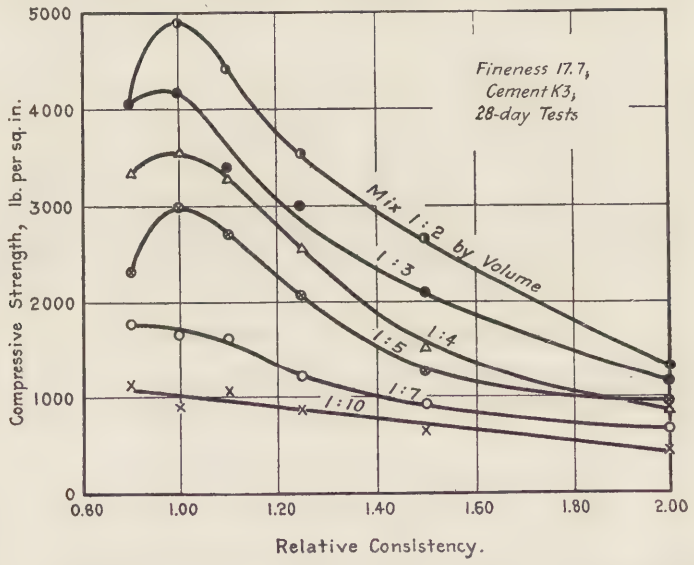


FIG. 30—EFFECT OF CONSISTENCY ON THE STRENGTH OF CONCRETE—SERIES 120.

Compression tests of 6 by 12-in. cylinders. Cement K-3.
See Table 23.
Similar diagrams may be platted for the other cements.

The yield is increased for the richer mixtures and for aggregates of small sizes.

The density of concrete is computed on the basis of the total volume of solids in the mass. For ordinary mixtures, such as 1:5 or 1:4, for usual consistencies, the density is about 0.82. The density is decreased by wet consistencies or aggregates of small size. Maximum density is found with mixtures of about 1:7.

Slump Tests for Workability.—The slump tests were carried out on all specimens in Series 118 and 120. The apparatus used in making this

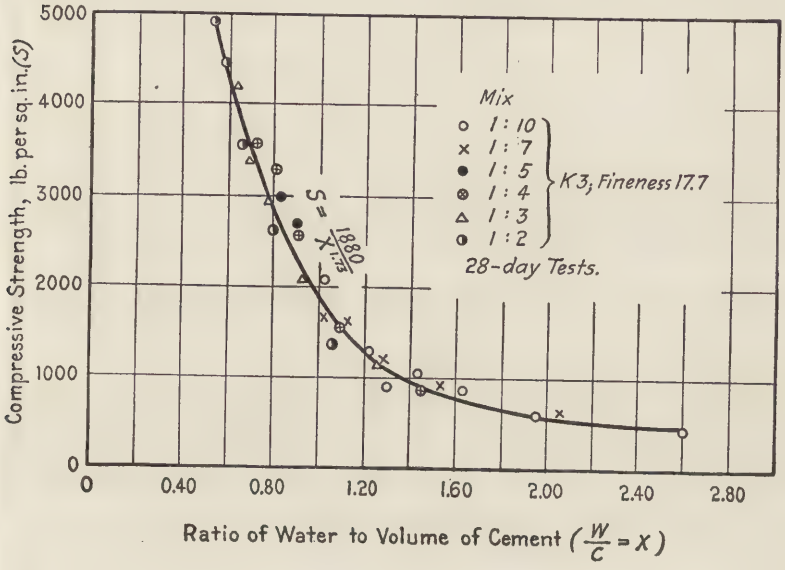


FIG. 31—WATER-RATIO-STRENGTH RELATION FOR CEMENT K-3—SERIES 120.

Compression tests of 6 by 12-in. cylinders. See Tables 23 and 25.

Similar diagrams may be platted for the other finenesses of Cement K.

test is shown in Fig. 1. The data from slump tests on these series are given in Tables 21, 30 and 31. Each value is the average of 3 to 5 determinations made on different days. The values for the 1:1¾ mixes in Series 118 are platted in Fig. 24. The slump is greatly increased for the wetter consistencies, but the fineness of the cement has little influence. It will be noted that the water proportioning was not exactly correct, since the curve for a relative consistency of 1.00 should have been horizontal, whereas it shows a slight inclination.

Slumps for Series 120 are given in Fig. 33. It should be noted that these curves are based on the average of 6 different mixtures. The tables

show that the leaner mixtures and the wetter consistencies are more affected by fineness of grinding of cement than are the mixtures of usual composition. In general, it may be said that for the richer mixtures and the consistencies usually used in building construction the fineness of the cement has no appreciable effect on the workability of concrete as determined by the slump test.

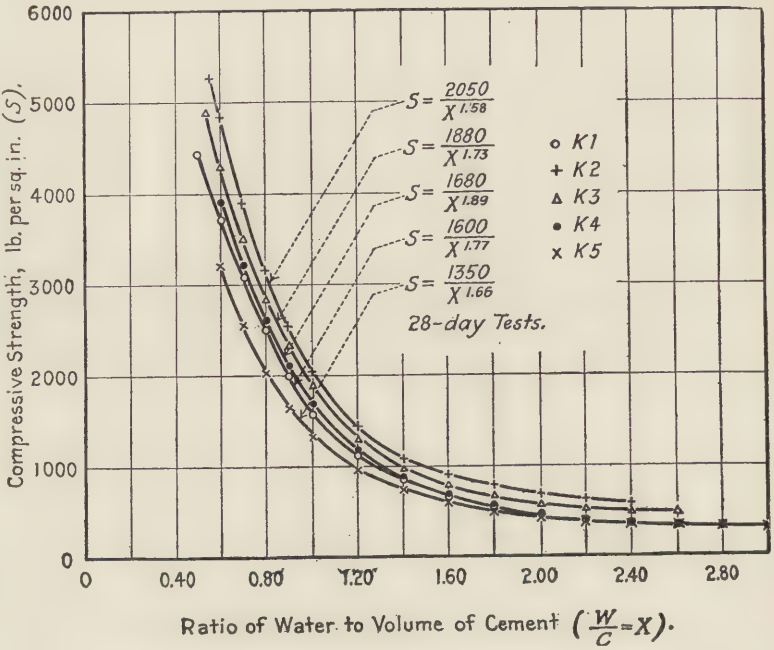


FIG. 32—WATER-RATIO-STRENGTH RELATION FOR CEMENTS K—SERIES 120.

Compression tests of 6 by 12-in. cylinders. See Tables 23 and 25.
Curves constructed from diagrams similar to Fig. 31.

Unit Weight of Cement.—The unit weight of cement was greatly changed by the fineness of grinding. Fig. 20 gives the relation between the weight and fineness for Cements K and L. The finer the cement the less the unit weight. For the cements used in these tests, unit weights varied from 76 (residue 2.4 per cent) to 108 lb. per cu. ft. (residue 43.3 per cent). The different cements gave quite similar results in this respect. For the usual range in fineness the weight is lowered ¾ lb. per cu. ft. for each 1 per cent decrease in residue on the No. 200 sieve. It should be noted that in using 94 lb. per cu. ft. as a uniform basis for proportioning,

as was done in all tests, the *volume* of the cement in the batch varies as much as 35 per cent. If the concrete had been proportioned in a manner to give a uniform *volume* of cement the comparisons would not have been so favorable to the finer cements. It is interesting to note that early cement specifications were based on the theory that the heavier cement was superior, yet at the same time they insisted on fine grinding. These two requirements are, of course, contradictory.

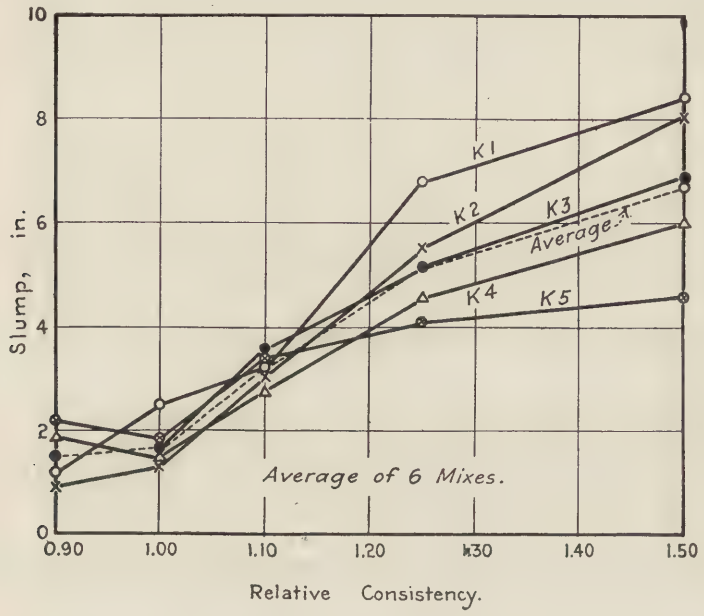


FIG. 33—EFFECT OF CONSISTENCY ON THE WORKABILITY OF CONCRETE—SERIES 120.

"Slump" tests of 6 by 12-in. cylinders made with apparatus shown in Fig. 1. Cement K. See Table 31.
Each value is the average of 30 tests from 6 mixes.

Normal Consistency of Cement.—The normal consistency of cement (by weight) is increased with fineness. The different cements gave quite similar results in this respect. The normal consistency is increased about 0.1 per cent (in terms of weight of cement) for each 1 per cent reduction in residue on the No. 200 sieve. The normal consistency *by volume* is only slightly increased with the fineness of grinding. Normal consistency by volume is the same as the water-ratio for neat cement.

Time of Setting of Cement.—A study of the effect of fineness on the time of setting of cement may be made from the results in Table 4. The Vicat needle tests for initial sets were somewhat erratic; however, the results clearly show a marked reduction in the setting time with the finer grinding of cement. In some instances the time of set is reduced to such an extent that the cement probably could not be used in construction work.

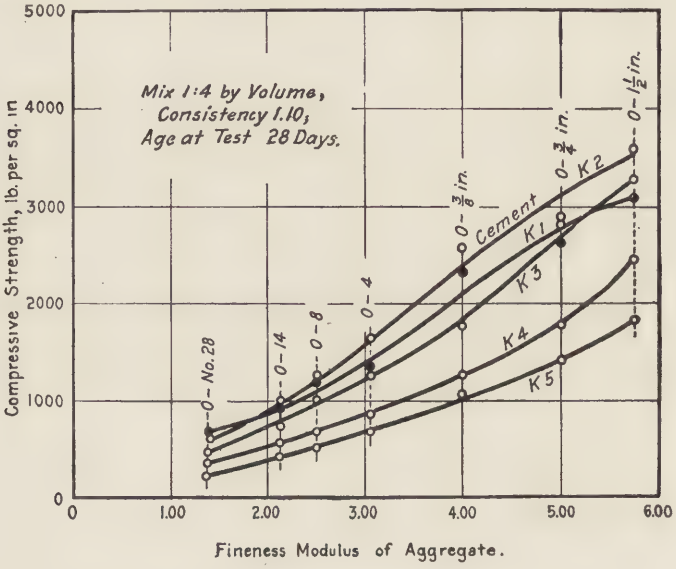


FIG. 34—EFFECT OF SIZE OF AGGREGATE ON THE STRENGTH OF CONCRETE—SERIES 120.

Compression tests of 6 by 12-in. cylinders. Cement K. See Table 26.

Similar diagrams may be constructed for the 7-day and 3-month tests.

Type of Aggregate.—Three distinct types of aggregate were used in these experiments. The bulk of the tests were made with sand and pebbles. Tests in Series 118 included burnt shale and crushed blast-furnace slag. The effect of fineness of cement appears to be independent of the nature of the aggregate.

SUMMARY AND CONCLUSIONS.

A summary of the investigations and the principal conclusions are given at the beginning of this paper.

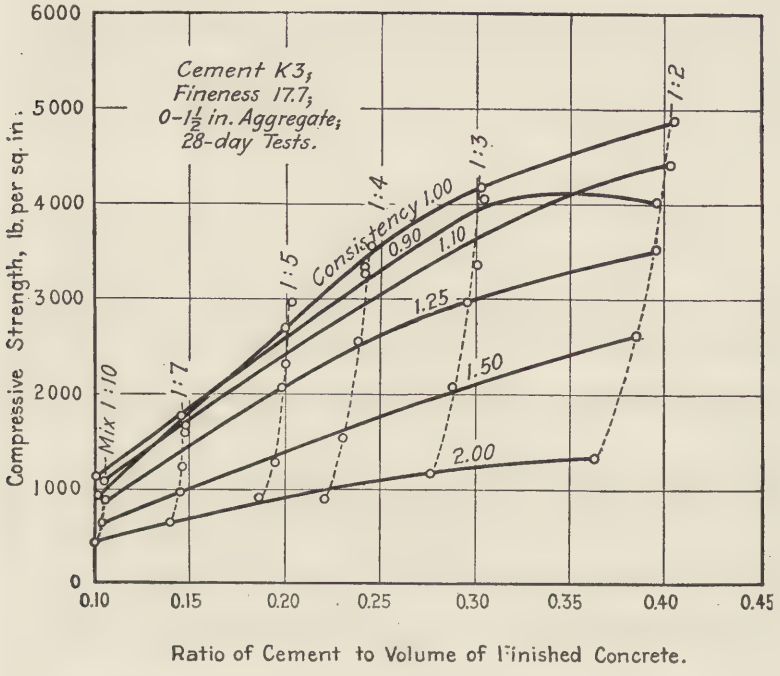


FIG. 35—EFFECT OF QUANTITY OF CEMENT ON THE STRENGTH OF CONCRETE—SERIES 120.

Compression tests of 6 by 12-in. cylinders. Cement K-3. See Table 23.

Similar diagrams may be constructed for the other finenesses of Cements K and L.

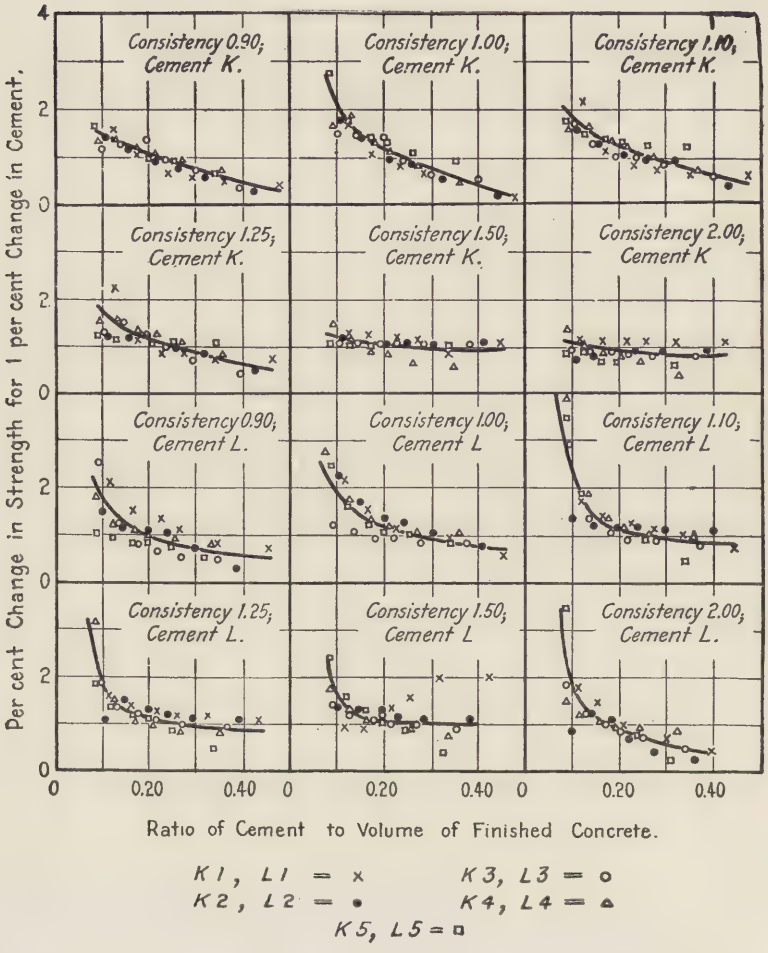


FIG. 36—CHANGE IN STRENGTH OF CONCRETE WITH QUANTITY OF CEMENT—SERIES 120.

Compression tests of 6 by 12-in. cylinders. Compare Fig. 13 and 14.

Cements K and L. Age at test 28 days.

Values determined from curves similar to those in Fig. 35.

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Bulletin 5

Structural Materials Research Laboratory
Lewis Institute
Chicago

Modulus of Elasticity of Concrete

By

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(Authorized Reprint from the Copyrighted Proceedings of the American Society for Testing Materials, Vol. XIX, Part II, 1919)

With an Appendix on the

Flexure of Reinforced Concrete Beams

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Revised Edition—April, 1923

FOREWORD TO REVISED EDITION

This report was originally published in the copyrighted Proceedings of the American Society for Testing Materials, Vol. XIX, Part II, 1919. Acknowledgment is made to the Society for permission to reprint the paper in bulletin form.

The oral and written discussions which appeared in the Proceedings are omitted from this Bulletin.

In issuing this revised edition, Tables 1, 4, 14 and 15, and Figures 11, 19, 21, 23, 24, 30, 32 and 33 have been revised to include tests at ages of 2 to 5 years. Only a few minor editorial changes have been made in the text. Attention is called to some of these changes in foot notes. No changes in the original discussion or general conclusions have been made necessary by the addition of data of the long-time tests.

Appendix A, "Flexure of Reinforced Concrete Beams" has been reproduced from the first edition, with only a few minor editorial changes.

The following Bibliographies have been added to the revised edition:

Appendix B, "Modulus of Elasticity of Concrete,"

Appendix C, "Modulus of Elasticity of Stone and Other Non-Metallic Materials of Construction."

MODULUS OF ELASTICITY OF CONCRETE.

By Stanton Walker

SUMMARY.

Little information has been available concerning the fundamental laws that govern the elastic properties of concrete. Values of modulus of elasticity are used in the design of reinforced concrete structures, from a simple beam to the complicated members of a concrete ship. Knowledge of proper values of modulus of elasticity is, therefore, most important to obtain a rational design.

This report summarizes compression tests on about 4000 6 by 12-in. concrete cylinders. The relation between the modulus of elasticity and strength of concrete was studied for the following variables: size and grading of aggregate, kind of aggregate, quantity of cement, consistency of concrete, age at test, time of mixing, and curing conditions of concrete. The tests show that the modulus of elasticity is affected by these variables in the same manner as the strength. Tests are reported which show that the gage lengths over which the deformations are measured have little effect on the value of the modulus of elasticity.

A number of equations have been offered as showing the relation between stress and deformation of concrete under load. A study of the stress-deformation data for our tests shows that this relation may be represented by the equation,

$$s = Kd^n \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where s = unit stress of concrete, d = unit deformation of concrete, K = a constant depending on the strength of the concrete, and n = an exponent, approximately constant.

This equation applies for stresses below 50 to 90 per cent of the ultimate strength, or below what may be termed the "yield point" of the concrete.

There is a general belief that the ratio between the modulus of elasticity and compressive strength of concrete is approximately constant. Tests on concrete of a number of different consistencies, sizes and gradings of aggregate, mixes ranging from 1:15 to neat cement, and ages ranging from 7 days to 5 years, show that there is a general relation between modulus of elasticity and strength of concrete for mixtures leaner than about 1-3, but that this relation is not linear. The relation may be represented by an equation of the form,

$$E = CS^m \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

where E = modulus of elasticity of concrete, C = a constant depending on the

conditions of the test, S = compressive strength of concrete, and m = an exponent.

Four different measures of modulus of elasticity of concrete are in more or less common use, as follows:

E_i ..... "Initial tangent" modulus;
E_t ..... "Tangent" modulus at some load;
E_s ..... "Secant" modulus to some load;
E_d ..... "Chord" modulus between two loads.

The initial tangent modulus for usual concrete mixtures may be represented by the equation,

$$E_i = 33\,000\,S^{\frac{3}{2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots (13)$$

For the tangent modulus at 25 per cent of the compressive strength Equation (13) becomes,

$$E_{t25} = 66\,000\,S^{\frac{1}{2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots (14)$$

A nomographic chart showing the inter-relation of mix, consistency, size and grading of aggregate, strength, and modulus of elasticity is presented.

A study of data from other sources shows that the stress-deformation relation of a great number of other materials, including various woods, metals, stone, brick, brick piers, rubber, rope, and concrete of many kinds, may be represented by a relation of the same form as that given for concrete in Equation (1).

MODULUS OF ELASTICITY OF CONCRETE

Introduction

Values of modulus of elasticity of concrete are used in the design of reinforced-concrete structures, from a simple beam to the complicated members of a concrete ship. This means that knowledge of proper values of modulus of elasticity is secondary only to knowledge of proper values of strength if a rational design is to be made. The small amount of available data on this subject has encouraged the writer to present the material contained in this report.

These tests were made as a part of the experimental studies of concrete and concrete materials being carried out through the co-operation of Lewis Institute and the Portland Cement Association at the Structural Materials Research Laboratory, Lewis Institute, Chicago.

Modulus of elasticity is usually defined as the ratio of unit stress to unit deformation within the proportional limit. If this definition is interpreted strictly, materials that are not perfectly elastic can have no modulus of elasticity. We therefore prefer to define modulus of elasticity as:

> The ratio of an increment of stress to a corresponding increment of deformation.

This definition is general for all materials, whether or not they are perfectly elastic. In this sense only perfectly elastic materials have a *constant* modulus of elasticity. Let us apply this definition to the modulus of elasticity of concrete.

There are in more or less common use four distinct measures of this quantity. They are as follows:

1. The "initial tangent" modulus (E_i); the modulus of elasticity determined by the ratio of stress to deformation as given by a tangent to the stress-deformation curve near its beginning. It will be shown that the so-called initial tangent is equivalent to a secant drawn to 5 to 15 per cent of the compressive strength.

2. The "tangent" modulus (E_t); the modulus of elasticity determined by the ratio of stress to deformation as given by a tangent to the curve at some stress, ordinarily the working load.

3. The so-called "secant" modulus (E_s); the modulus of elasticity determined by the ratio of stress to deformation as given by a line drawn from the origin of the curve to some stress, ordinarily the working load.

4. The "chord" modulus (E_d); the modulus of elasticity determined by the ratio of stress to deformation as given by the chord drawn between two points on the curve, ordinarily defined by the limits of stresses for working loads. It will be noted that the chord modulus (E_d) is almost identical with the tangent modulus (E_t), hence no study of it is presented.

Fig. 1 shows the graphical conception of the above measures of modulus of elasticity. The relation shown must not be taken as typical since it was necessary to exaggerate the curvature for purposes of reproduction.

The experimental data presented in this report are based on compression tests of 6 by 12-in. concrete cylinders made in 9 different series of investigations carried out over a period of about 18 months and comprising a total of about 10,000 specimens. Details are given of the results of about 4000 tests covering the effect of the following variables on the modulus of elasticity.

(*a*) Size and grading of aggregate (fine sands to well-graded concrete aggregates);

(*b*) Quantity of cement (mixtures varying from 1:15 to neat);

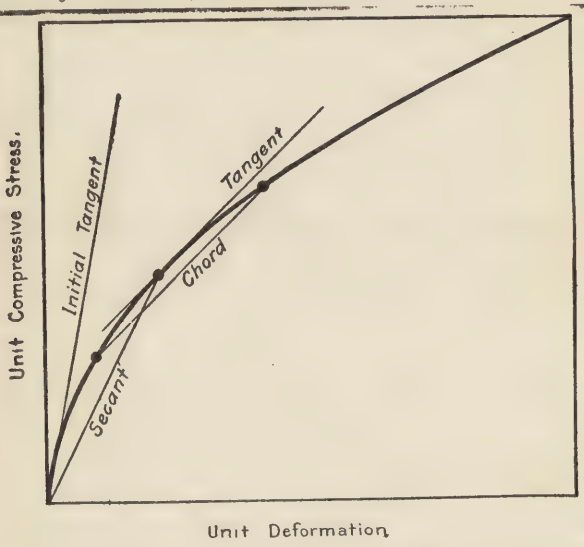


FIG. 1—Four Methods of Determining Modulus of Elasticity from Stress-Deformation Curve.
Curvature is exaggerated to bring out these relations clearly.

(*c*) Quantity of mixing water (relative consistencies ranging from 0.70 to 2.00);

(*d*) Age at test (7 days to 5 years);

(*e*) Kind of aggregates (pebbles, granite, limestone, and blast furnace slag);

(*f*) Curing condition of concrete;

(*g*) Time of mixing concrete.

Studies were also made to show the variation in modulus of elasticity as affected by:

(*h*) Stress at which modulus of elasticity is measured (up to 50 per cent of the compressive strength of the concrete);

(*i*) Method of calculating modulus of elasticity;

(*j*) Gage length over which deformations were measured (4 to 10-in. on a 6 by 12-in. cylinder).

In general the data on modulus of elasticity were obtained in the course of investigations carried out with other objects in view.

These tests establish the form of the stress-deformation relation for concrete. This relation offers an accurate method for the determination of modulus of elasticity, and shows the characteristics of the various measures of this function. These tests show that the modulus of elasticity and strength of concrete are affected in a similar manner by the variables mentioned above. For a wide range in mixtures, consistencies, ages, etc., the relation between modulus of elasticity and strength may be represented by a single curve.

ACKNOWLEDGMENT

Acknowledgment is made to the firms mentioned below for their courtesy in donating the aggregates, and to M. Kaplan and H. L. Flodin, of the Laboratory staff, for assistance in working up and interpreting the data.

MATERIALS

The portland cement used in these tests consisted of a mixture of equal parts of 4 brands purchased in Chicago. The brands were thoroughly mixed by placing one sack of each in a concrete mixer and running for about 1 minute. Details of tests of cement are given in Table 1.

The aggregates used were as follows:

Sand and pebbles from the Chicago Gravel Co., Elgin, Ill.;

Crushed limestone from the Artesian Stone and Lime Works Co., Chicago;

Crushed blast furnace slag from the Illinois Improvement and Ballast Co., Chicago;

Crushed granite from the Wisconsin Granite Co., Berlin, Wis.

Miscellaneous tests of the aggregates are given in Table 2.

The water was from the city water supply obtained from Lake Michigan.

PROPORTIONING AND MIXING CONCRETE.

All mixtures were by dry volume; they are referred to as one volume of cement to a given number of volumes of mixed aggregate. No distinction is made between what are generally termed mortar and concrete mixtures.

The weight of cement was assumed as 94 lb. per cu. ft.

The weight per cubic foot of the aggregate was determined by measuring in a machined cast-iron measure having a capacity of $\frac{1}{5}$ cu. ft. and inside diameter equal to the depth. The test was made by filling the measure about $\frac{1}{3}$ full and puddling with a $\frac{5}{8}$-in. round steel bar pointed at the lower end. Filling and puddling were continued in like manner until the measure was full. After striking off with a straight edge, the weight was determined. This is

the method recommended by Committee C-9 on Concrete and Concrete Aggregates of the American Society for Testing Materials.[a]

The hand-mixed concrete was mixed in the manner regularly followed for making such tests in this Laboratory. Each specimen was made from a batch of about 1/5 cu. ft., which was proportioned separately and mixed with a bricklayer's trowel in a shallow metal pan. The machine-mixed concrete was mixed in a 3½ cu-ft. Smith "Mascot" mixer.

The amount of mixing water is expressed as the ratio of volume of water to volume of cement. This so-called "water-ratio" has been shown by Abrams[b] to be the best criterion of the strength of concrete.

The term "consistency" is used to denote the plasticity of the concrete. This value is relative and does not indicate the actual amount of mixing water. The consistency called normal (relative consistency, 1.00) is of such a plasticity that a 6 by 12-in. concrete cylinder of ordinary mixtures will slump ½ to 1 in. upon the removal of the metal form by a steady upward pull immediately after molding the specimen.[c] An addition of 10 per cent of water (relative consistency, 1.10) will give a slump of 5 to 6 in. A relative consistency of 1.25 will cause a slump of about 8 to 9 in. The uniformity with which the slump can be determined varies considerably with the richness of the mix and nature of the aggregate.

TEST SPECIMENS.

Specimens were made in cylindrical steel forms, 6 in. in diameter and 12 in. long. The concrete was puddled in a manner similar to that described above for determining unit weights of aggregates. The forms were placed on machined cast-iron base plates to insure a plane bearing surface for the bottom of the cylinder. Two or three hours after finishing, a thin layer of neat cement paste mixed before the cylinder was molded, was placed on the top of the specimen and a smooth surface formed by means of a glass plate. In general, the values for hand-mixed concrete are the average of 5 specimens made on different days. The values for machine-mixed concrete are the average of 4 specimens from different parts of the same batch.

In general, test specimens were stored in damp sand until the day of test; 2 to 5-year test pieces were cured in a moist room after age of about 1 year.

COMPRESSION TESTS OF CONCRETE.

All specimens were tested in a 200 000-lb. Olsen universal testing machine. A spherical bearing block was used to obtain an even distribution of the load. In general, deformation readings were taken at each 100-lb. increment up to

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a. (Note to Revised Edition.) This method is now standard under the title "Standard Method of Test for Unit Weight of Aggregate for Concrete," Serial Designation C20-21.

b. See "Design of Concrete Mixtures," by D. A. Abrams, Bulletin 1, Structural Materials Research Laboratory.

c. (Note to Revised Edition.) Present practice in making the slump test for consistency or workability of concrete requires the use of a 4 by 8 by 12-in. truncated cone. For concrete of a given consistency the cone gives slumps about ⅔ that of the cylinder. The truncated cone is specified in the Progress Report of the Joint Committee on Standard Specifications for Concrete and Reinforced Concrete and is used in the Tentative Method of Tests for Consistency of Portland-Cement Concrete for Pavements or Pavement Base of the American Society for Testing Materials. Serial designation D138-22T.

1000 lb. per sq. in., and at each 500 lb. per sq. in. thereafter until near failure. For tests reported in Tables 4 to 12 at ages of 1 year or less, readings were taken with the head of the machine traveling about 0.01 in. per minute. For tests in Tables 13 and 14 and for the long time tests in Tables 4 to 12, test loads up to 50 to 75 per cent of the ultimate strength were applied with the head of the machine traveling about 0.05 in. per minute. Above this point a speed of 0.01 in. per minute was used. The machine was stopped at each increment of stress long enough to read the deformation accurately. A special investigation has shown that the rate of applying the load below 50 to 75 per cent of the ultimate has no effect on the strength.[1] The advantage of the latter method is that more tests can be made in a given time with no sacrifice of accuracy. Deformations were measured over a 6-in. gage length for all tests except those reported in Table 12.

EXTENSOMETERS USED IN CONCRETE TESTS.

A detail drawing of the instrument used for most of the tests reported in this paper is given in Fig. 2. This instrument differs from those used in certain other laboratories in 5 essentials:

1. The bottom yoke is attached to the specimen by 3 pointed set screws. The design allows no movement of this yoke, thus stabilizing the instrument.

2. The deformation is measured by an Ames dial reading to 0.0001 in.

3. The average deformation of the cylinder is indicated on a single dial.

4. The deformation is transmitted to the dial by means of a stiff steel rod.

5. The dial is held in place by a self-seating wing nut and can be readily removed before failure of the specimen.

The spacing bars shown in the plan are removed after the instrument is attached to the cylinder. The distance bar *A* maintains one side of the yokes in a fixed relation to each other. This arrangement causes the top yoke to rotate about its points of contact as the specimen is compressed. Twice the total deformation of the specimen is transmitted to the Ames dial.

This instrument was used on all tests except those reported in Series 89, Table 5, about one-half of the tests for ages less than a year in Series 93 (Tables 6, 7 and 8), and on all tests at ages less than a year in Series 83 (Table 4).

The instrument used in the earlier tests had the same frame as that shown in Fig. 2 except that there were only two set screws in the bottom yoke. A Johnson wire-wound dial was used in place of the Ames dial. The face of this instrument is divided in such a manner that direct readings of 0.001 in. can be made; a vernier makes possible readings to 0.0001 in. The arc representing 0.001 in. deformation on the Johnson instrument is about equal to that representing 0.000025 in. deformation on the Ames. Aside from the difference in the divisions of the dial faces, the Johnson instrument is not as sensitive as

[1]See "Effect of Rate of Application of Load on the Compressive Strength of Concrete," by D. A. Abrams, Proc. Am. Soc. Testing Mat., Vol. XVII, Part II, p. 364 (1917).

the Ames. Movement of the indicator on the Johnson instrument is caused by a fine wire. There is always a certain amount of slack in the wire, and slip about the drum of the dial. This slack and slip is sometimes sufficient to

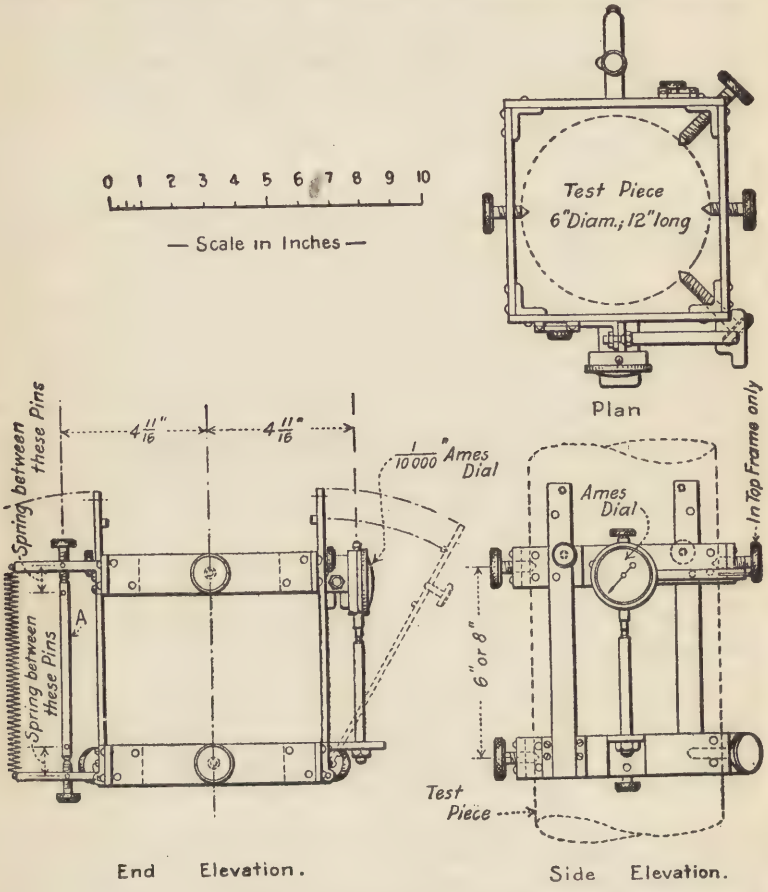


FIG. 2.—Extensometer for Compression Tests of 6 by 12 in. Concrete Cylinders.

cause a stress-deformation curve with an increasing slope, a relation which is not found in concrete and which is characteristic of only a few materials such as rubber.

STRESS-DEFORMATION RELATION.

There appears to be no general agreement among writers as to the form of the stress-deformation relation for concrete. Some writers are of the opinion that for the lower loads this is represented by a straight line; while most writers hold that there is a decreasing slope from the beginning.

A number of formulas have been offered as representing the relation between stress and deformation for concrete. The tests reported in this paper, and several thousands not included, indicate that this relation is of the form,

$$s = Kd^n \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where s = unit stress in the concrete, d = unit deformation of concrete, K = a constant depending on the strength of the concrete, and n = an exponent, approximately constant.

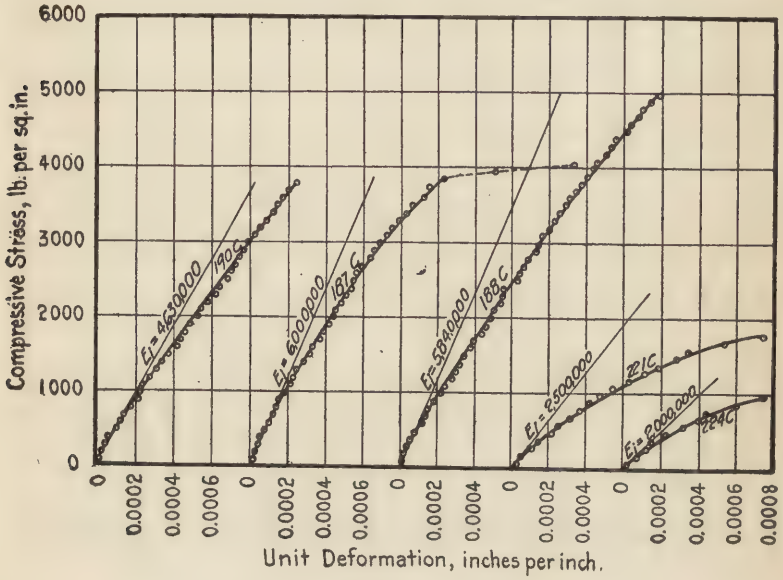


FIG. 3.—Typical Stress-Deformation Curves for Concrete.

Data from Table 3.
Compression tests of 6 by 12-in. cylinders.
Mix 1 : 4.
Sand and pebble aggregate.
Gage length 6 in.
The following table gives further details of the tests:

Ref. No.	Size of Aggregate	Relative Consistency	Compressive Strength at 3 m. lb. per sq. in.
187-c	0–1½	0.90	4010
188-c	0–1½	1.00	5210
190-c	0–1½	1.25	4200
221-c	0–8	1.10	1890
224-c	0–8	1.10	1060

Bach gives a similar law. Mörsch[1] says, "The deformation curves found by Bach are so regular that they may be represented by an exponential equation, the relation between compression and stress being such that

$$d = as^r \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where d = unit deformation of concrete, a = a constant, s = unit stress in concrete, and r = an exponent."

Eq. 2 is of the same nature as Eq. 1 and can readily be converted to the same form.

Fig. 3 gives typical stress-deformation diagrams for concrete tested in this Laboratory. It is known from mathematical considerations that an equation

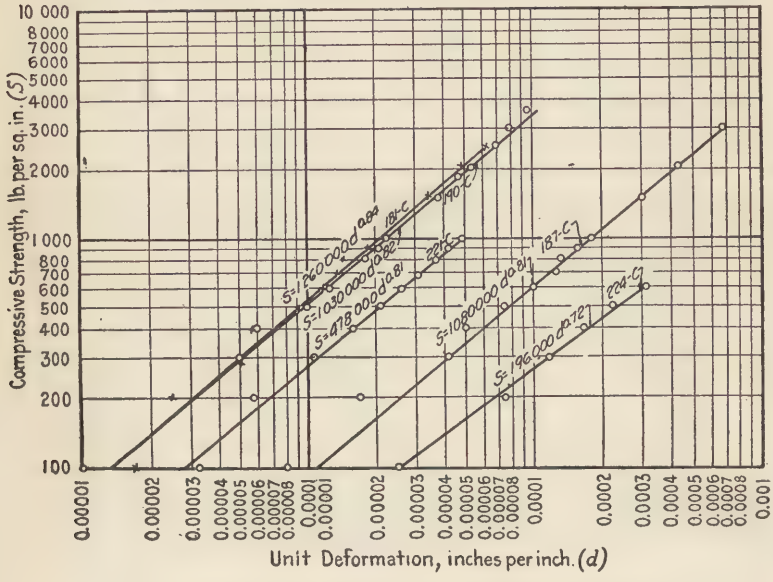


FIG. 4.—Typical Stress-Deformation Curves for Concrete.
Same data as in Fig. 3, platted to logarithmic scales.

of the form of Eq. 1 or 2 will give a straight line when platted on logarithmic co-ordinates. Fig. 4 gives the same data as Fig. 3, except that stresses and deformations are platted to logarithmic scales. All of the curves give straight lines, thus showing that they may be represented by the form given in Eq. 1 and 2 within the range of readily measured loads and below stresses of 50 to 90 per cent of the compressive strength. In general, the exact location of the point where this law no longer holds was not definitely determined, due to the necessity of removing the Ames dial before failure of the specimen. It seems probable that this point is approximately the same as the "yield point" men-

[1]See "Concrete-Steel Construction" (Translation of Mörsch's "Der Eisenbetonbau"), by E. P. Goodrich.

tioned by certain writers. The determination of "yield point" is discussed in detail on page 48.

For the data given in Fig. 3 and 4, measurements were taken at shorter intervals for the higher loads than is our custom, for the purpose of showing more definitely the range over which the law given in Eq. 1 holds. The values of initial tangent modulus given in Fig. 3 should not be taken as necessarily typical for the concrete used, since only one specimen is represented in each curve.

Table 3 illustrates the manner in which the deformations for typical concrete as calculated by Eq. 1 compare with the measured deformations. The data for this table are from the same tests as those given in Fig. 3 and 4.

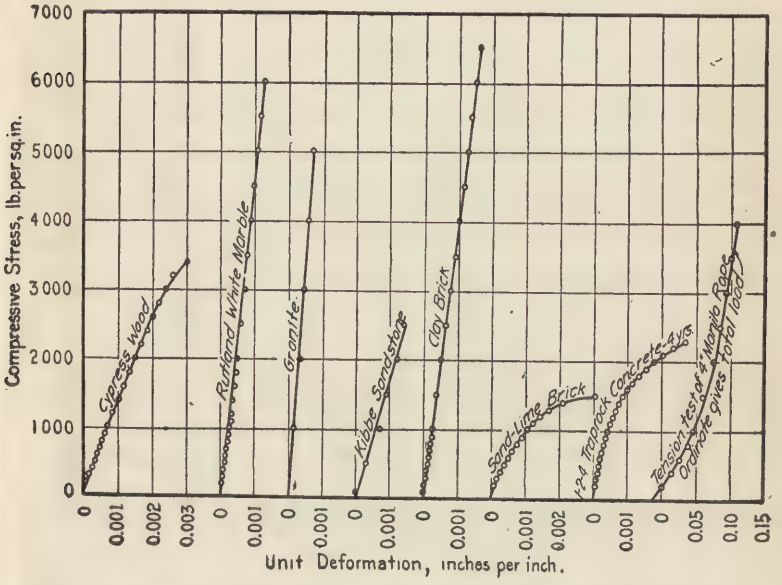


FIG. 5.—Typical Stress-Deformation Curves for Miscellaneous Materials.
Data from "Tests of Metals" (Watertown Arsenal, 1895 to 1904).

Having determined the constants required for Eq. 1, the unit deformations were calculated for the stresses shown. The calculated values give a satisfactory agreement with those determined in the test.

The law expressed by Eq. 1 has been found to hold for other materials as well as for concrete. Fig. 5 and 6 show stress-deformation curves for several materials, platted from data found in "Tests of Metals" (Watertown Arsenal, 1895 to 1904). Fig. 7 and 8 show the same curves platted to logarithmic scales. The curves platted in this form give straight lines, consequently they may be represented by a function of the type of Eq. 1. Data from numerous other tests were platted and found to follow the same law. These tests

included various woods, metals, stone, brick, brick piers, rubber, rope, and concrete of many kinds. An unsuccessful search has been made for stress-deformation data from either compression or tension tests that do not follow this law. It appears, therefore, that the law stated above is general for all materials. Bach showed that this equation may be used to express the stress-deformation relation for certain materials other than concrete.

In studying data platted on logarithmic co-ordinates, it should be borne in mind that small discrepancies are apparently greatly exaggerated for the lower loads. On logarithmic coordinates the distance representing a change in

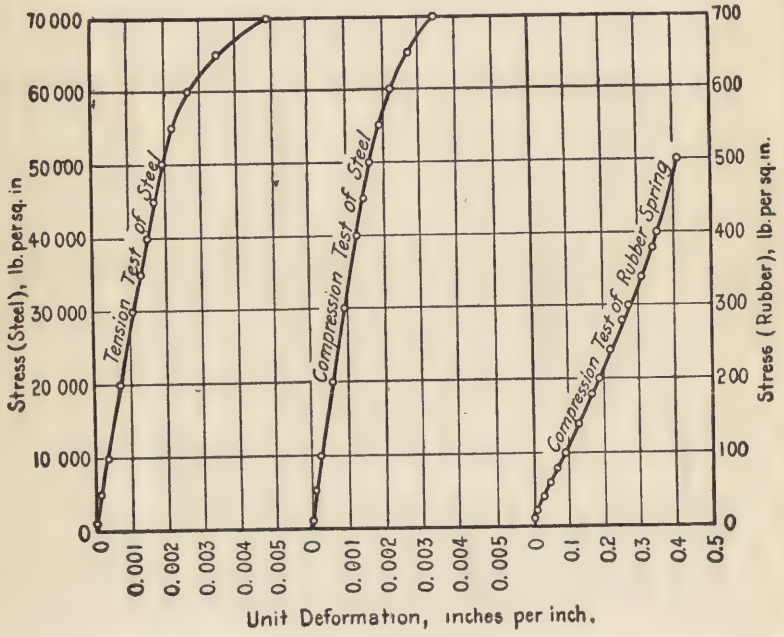


FIG. 6.—Typical Stress-Deformation Curves for Miscellaneous Materials.
Data from "Tests of Metals" (Watertown Arsenal, 1895 to 1904).

deformation from 0.0001 in. to 0.0002 in. is the same as that representing a change of 0.01 in. to 0.02 in., etc.

Methods of Calculating Modulus of Elasticity.—The methods of calculating the secant and chord moduli are apparent. The secant modulus is the stress divided by the deformation at a given load. The chord modulus is the difference in stresses divided by the difference in deformations over the chosen increment.

It is not easy to arrive at the tangent modulus accurately unless the form of the curve is known. Eq. 1 indicates that the true initial tangent modulus is infinity, if the equation holds to the origin of the stress-deformation curve.

Instruments of sufficient delicacy are not available to determine this, but since this equation represents the relation for measurable loads below the point called the "yield point," it appears altogether reasonable to conclude that it holds for the very low loads. If the stress-deformation curve is platted to an exaggerated scale, and a smooth curve drawn to the origin, it will be found that the curve is of the form shown by Eq. 1.

The slope of the tangent at a given point on a curve is the first derivative of the function representing this curve. This gives from Eq. 1,

$$E_t = \frac{\delta s}{\delta d} = nKd^{n-1} = \frac{nK}{d^{1-n}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

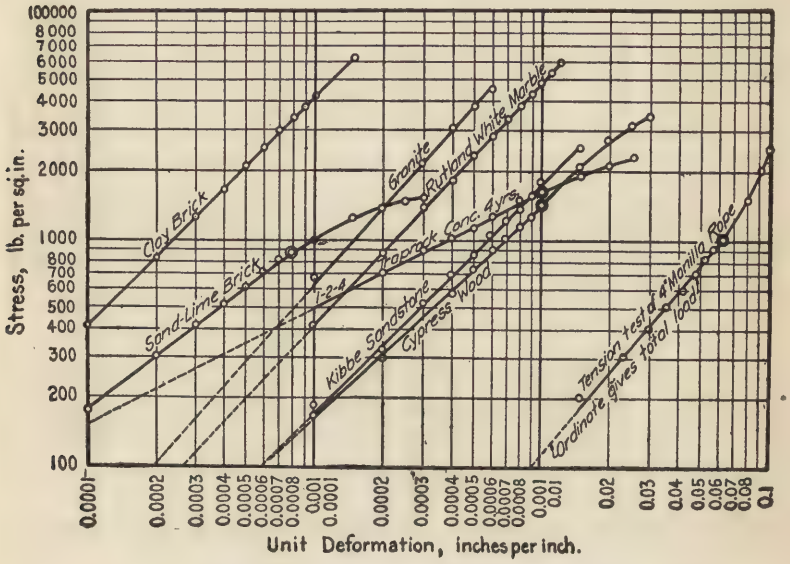


FIG. 7.—Typical Stress-Deformation Curves for Miscellaneous Materials.
Same data as in Fig. 5, platted to logarithmic scales.

Also,

$$\frac{s}{d} = \frac{Kd^n}{d} = \frac{K}{d^{1-n}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Substituting in Eq. 3,

$$E_t = \frac{ns}{d} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

By definition,

$$E_s = \frac{s}{d} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

Therefore,

$$E_t = nE_s \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

E_s can be obtained directly from the stress-deformation data. (See Eq. 6.) The most accurate method of determining n is to plat the stress-deformation curve to logarithmic scales. The logarithmic form is desirable since it affords a ready means of determining the average curve. It is much easier to draw a correct average line through points which may be represented by a straight line than through points which fall on a curved line, the degree of curvature of which is not known. When platting the stress-deformation data on logar-

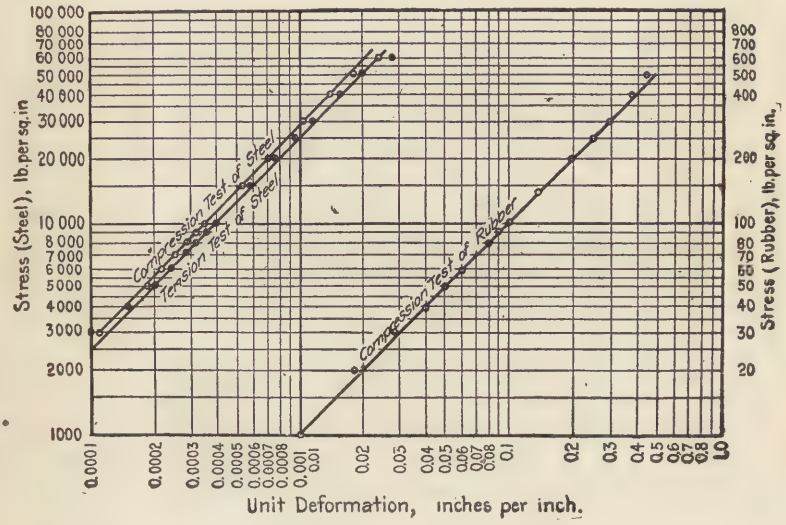


FIG. 8.—Typical Stress-Deformation Curves for Miscellaneous Materials.
Same data as in Fig. 6, platted to logarithmic scales.

ithmic co-ordinates, one must be sure that the instrument registered zero at zero load, or that the proper correction has been made. If care is not taken at this point the true relation will not be found. This Laboratory has found the use of the logarithmic co-ordinates most satisfactory in computing values of modulus of elasticity from the observed data.

Determination of Constants.—Having platted the stress-deformation curve on logarithmic co-ordinates, it is easy to determine the constants K and n. It may be well to give a brief description of the working method.

The exponent n is the slope of the straight line, measured by the logarithms of the stresses and deformations. It may be calculated as the logarithm of the ratio of the stress at any deformation to the stress at one-tenth of that deformation. K is the stress at a unit deformation of 1, expressed in pounds per square inch. It may be calculated easiest as the anti-logarithm of the

quantity $4n$ plus the logarithm of the stress at a unit deformation of 0.0001. For example, in Fig. 4 the value of n for Specimen 187 C may be calculated as the logarithm of the ratio of the stress at a unit deformation of 0.0002 to the stress at 0.00002. Then $n = \log. \frac{1080}{167} = 0.81$. For the same case K = anti-log. $(4 \times 0.81 + \log. 600) = 1\,040\,000$ lb. per sq. in.

It has been shown in Eq. 7 that n may be expressed as the ratio of tangent modulus to the secant modulus at the same load. In Fig. 9, 10 and 11 the

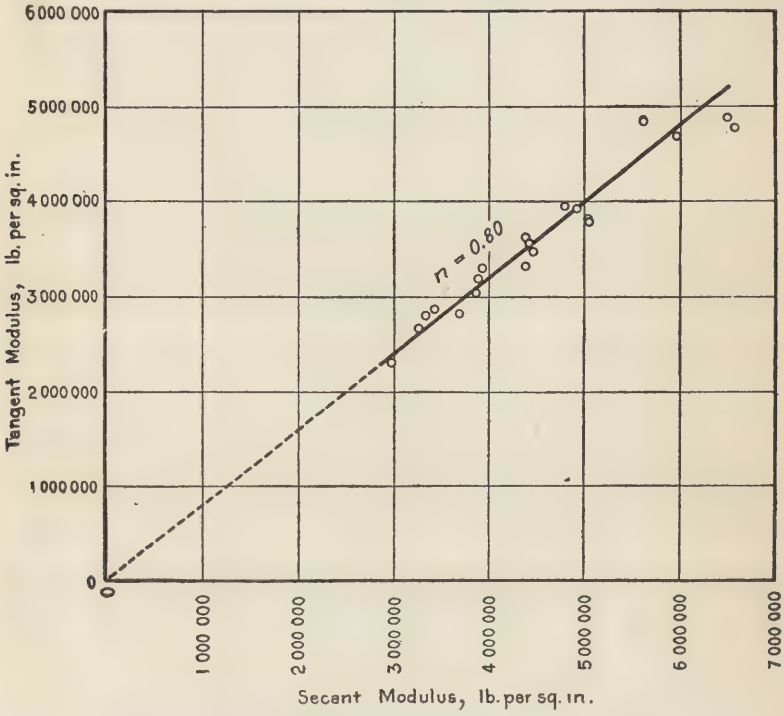


FIG. 9.—Relation of Tangent Modulus to Secant Modulus.

Average value of n for the tests in Table 12.
Based on 28-day compression tests of 6 by 12-in. cylinders for 4 mixtures.
Sand and pebble aggregate; graded 0–1½ in.
Relative consistency 1.00.
Each value is the average of 80 tests, 20 each from 4 gage lengths.
Compare Fig. 10 and 11.

secant modulus is platted against the tangent modulus. This relation is represented by a straight line passing through the origin. The slope of this line is the average value of n. These data are from Tables 12, 13 and 14. This indicates that for a given series of tests n is approximately constant. The relations shown in Fig. 9 and 11 are very uniform, while for Fig. 10 they are

somewhat less uniform. The graphically determined averages for n are 0.80, 0.90 and 0.92 for Fig. 9, 10 and 11, respectively.

K varies with the strength of the concrete and is greatly influenced by small changes in the value of n. Tables 12, 13 and 14 give values of K for concrete of different composition, age, etc. The values of K and n in the tables do not check exactly with the moduli of elasticity, due to the fact that average values determined from the tests are reported, instead of moduli from an average equation. It will readily be seen that the average constants of exponential equations do not give the same result as an average of the results

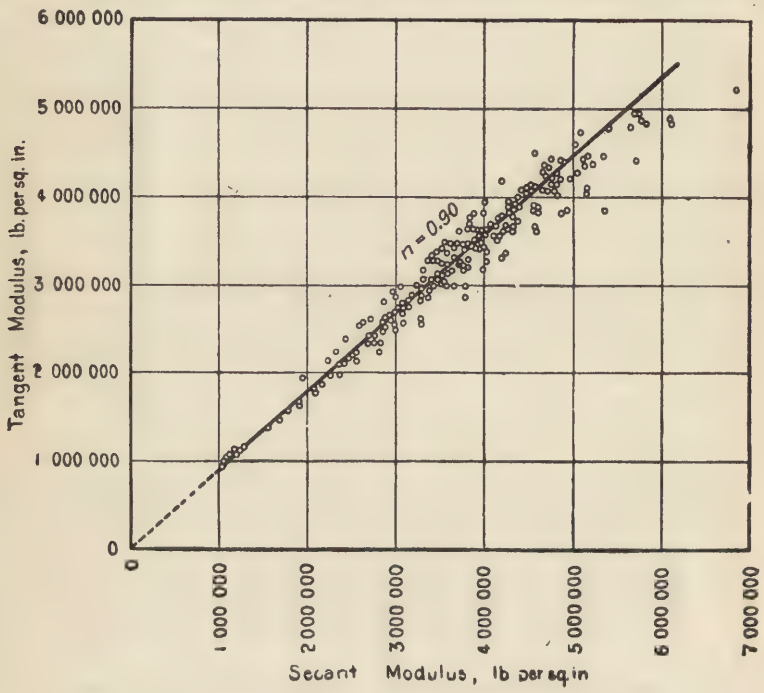


FIG. 10.—Relation of Tangent Modulus to Secant Modulus.

Average value of n for concrete in Table 13.
Based on 28-day compression tests of 6 by 12-in. cylinders for different mixtures, consistencies and gradings of aggregate.
Sand and pebble aggregate.
Compare Fig. 9 and 11.

of the individual equations. However, the difference is very small in this case, as the constants vary over a narrow range.

Nomographic Chart for Stress-Deformation Relation.—For material of a given composition under load, stress and deformation vary with a fixed relation to each other. Therefore, if the constants K and n are known and the stress is assumed, the corresponding unit deformation can be determined; or the

unit stress can be calculated if the unit deformation is assumed. Fig. 12 gives a nomographic chart for solving Eq. 1. In the example worked out on the chart K is assumed as 800 000 lb. per sq. in. and $n = 0.75$. For these conditions concrete stressed to 800 lb. per sq. in. would have a unit deformation of 0.0001. (For a discussion of the principles of nomographic charts see "Graphical and Mechanical Computation," by Lipka.)

DISCUSSION OF TESTS.

Tests are reported showing the effect of a number of different variables on the modulus of elasticity and strength of concrete.

Effect of Gage Length.—A series of tests was carried out for the purpose of discovering the influence of the gage length over which the deformations were

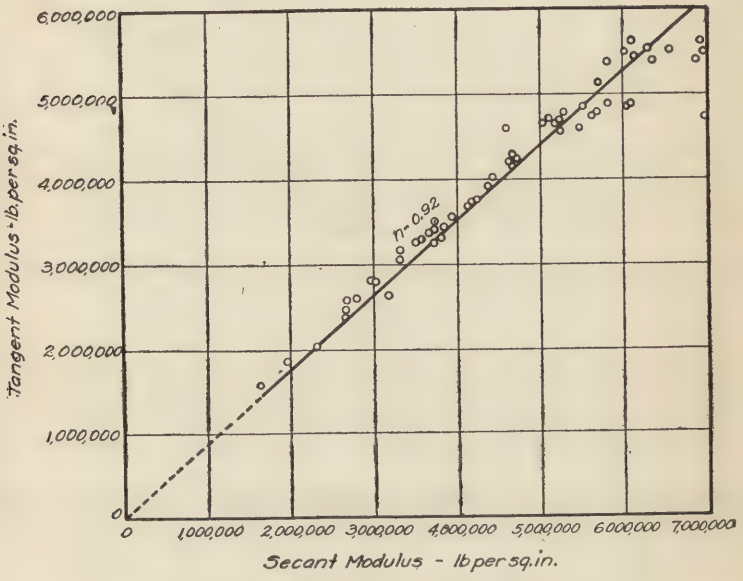


FIG. 11.—Relation of Tangent Modulus to Secant Modulus.

Average value of n based on tests of 6 by 12-in. concrete cylinders at 7 d., 28 d., 3 m., 1 y. and 2 y. for a wide range of mixtures, consistencies and gradings of aggregate. Sand and pebble aggregate.
Compare Fig. 9 and 10.

measured on the value of the modulus of elasticity of concrete when loaded in compression. This series included tests on concrete of 4 mixes: 1 : 7, 1 : 5, 1 : 4 and 1 : 3. The aggregate was sand and pebbles, graded 0–1½ in. The concrete was of normal consistency (relative consistency, 1.00). Each set of tests consisted of 20 specimens made on different days. Details of the data are given in Table 12. Measurements were taken over gage lengths of 4, 6, 8 and 10 in. on 6 by 12-in. cylinders. In Fig. 13 the average of all of the mixes is platted to show the effect of gage length. The tests show that the

gage length over which deformations were measured had little effect on the value of the elasticity, hence all of the values obtained for each mix have been averaged, thus securing moduli of elasticity and strengths based on 80 tests.

Effect of Grading of Aggregate.—A measure of the size and grading of aggregate, termed the *fineness modulus*[1], has been developed as a result of experimental work carried out in this Laboratory by Professor Abrams. The fineness modulus is the sum of the percentages in the sieve analysis, divided by 100, when the sieves shown in Table 2 are used. The sizes of sieves used and the method of recording the sieve analysis are given in Table 2. It has been shown that the fineness modulus may be used as a measure of the quantity

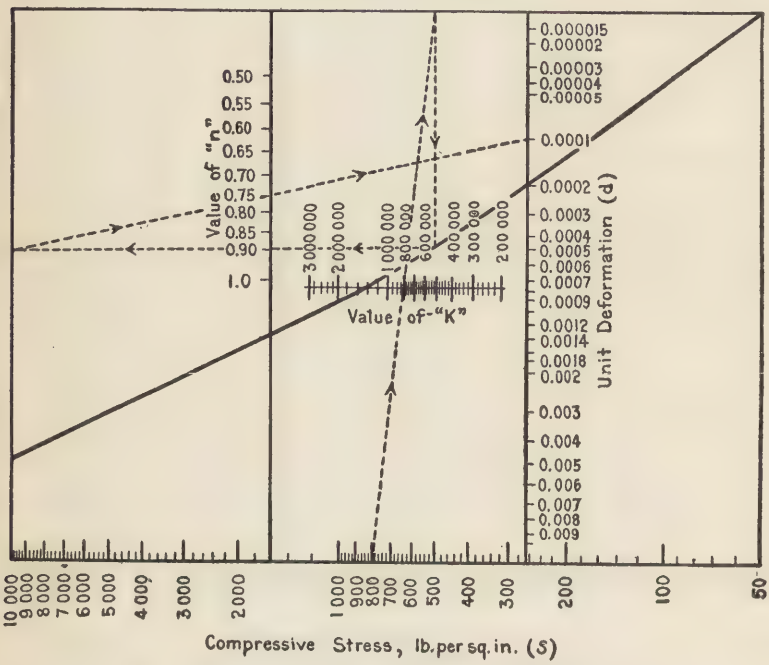


FIG. 12.—Nomographic Chart for Solving $s = Kd^n$.

of water necessary to produce concrete of a given plasticity using aggregates of different sizes and gradings.

Fig. 14 to 16, inclusive, show the effect of size and grading of aggregate on the modulus of elasticity and strength of concrete of various mixtures, ages, etc.

Fig. 14 shows the effect of size of aggregate on the strength and initial tangent modulus for a 1 : 5 mix and 1.10 consistency. The details of the tests

[1]For a discussion of this function, see "Design of Concrete Mixtures," by D. A. Abrams, *Bulletin 1*, Structural Materials Research Laboratory. See also "Examples of the Application of Abrams' Water-Ratio to Proportioning Concrete," by S. Walker, Proc. Am. Concrete Inst., 1920.

are given in Table 7. The importance of a well-graded aggregate is apparent from these curves. For example, for the 28-day tests the strength obtained from an ordinary torpedo sand is about 500 lb. per sq. in., while that obtained from the 0–1½-in. aggregate is 1800 lb. per sq. in., an increase of 260 per cent. For the same conditions the moduli of elasticity are 1 800 000 and 3 600 000 lb. per sq. in. respectively, or an increase of 100 per cent. The values from these tests are low, probably due to the fact that the specimens were made during the winter and stored in the basement where the temperature was somewhat low.

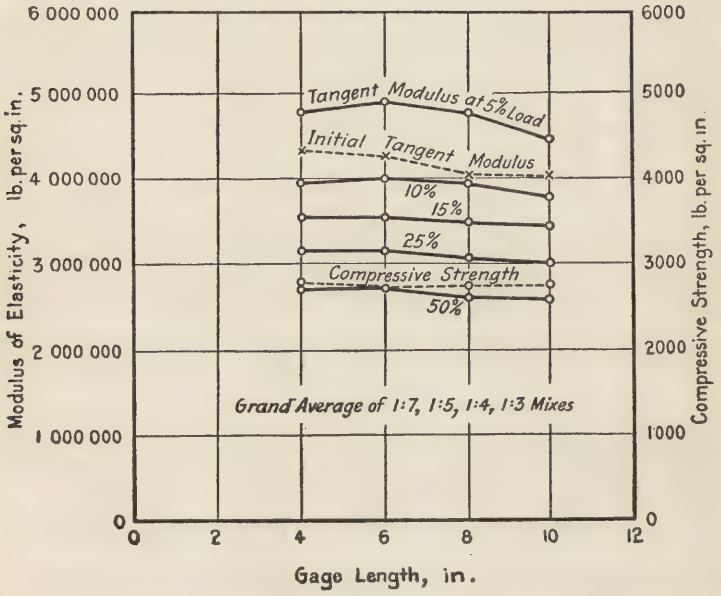


FIG. 13.—Effect of Extensometer Gage Length on the Value of the Modulus of Elasticity.

Data from Table 12.
28-day compression tests of 6 by 12-in. cylinders.
Sand and pebble aggregate; graded 0–1½ in.
Relative consistency 1.00.
Each value is the average of 80 tests, 20 each from 4 mixtures.

Fig. 15 gives additional data on the effect of size of aggregate on the modulus of elasticity at various percentages of the compressive strength for the average of the 1 : 3 and 1 : 5 mixes in the first and second groups of Table 13.

Fig. 16 shows the effect of varying the proportions of fine and coarse aggregate for a 1 : 5 mix and relative consistency of 1.00. The relation is shown for the strength, "initial tangent" modulus, and "tangent" modulus at stresses varying from 5 to 50 per cent of the compressive strength. These data illus-

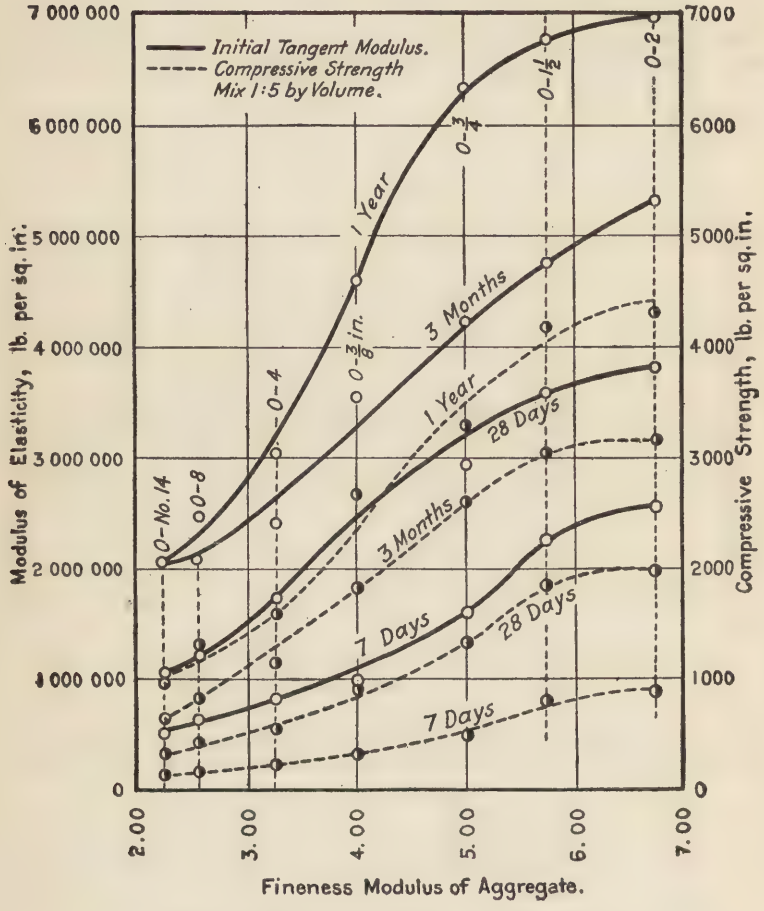


FIG. 14.—Effect of Size of Aggregate on Modulus of Elasticity.

Data from Table 7.
Compression tests of 6 by 12-in. cylinders.
Sand and pebble aggregate.
Relative consistency 1.10.
Each value is the average of 24 tests from 6 times of mixing.
Compare Fig. 15 and 16.

trate the importance of combining the fine and coarse aggregate in the proper proportions.

All of these curves show that both the modulus of elasticity and strength are greater for the coarser aggregates—higher fineness moduli—up to a certain point beyond which this relation does not hold.[1] Similar relations are found for data given in Tables 4, 8, 11 and 14. It will be noted that for each of the instances cited above, the modulus of elasticity increases less rapidly than the strength. It will be shown below that the other variables which affect the strength of concrete give a similar relation.

Effect of the Quantity of Cement.—Fig. 17 and 18 show the effect of the quantity of cement (the mix) on the strength and modulus of elasticity of concrete. The abscissas are quantities of the cement expressed as percentages

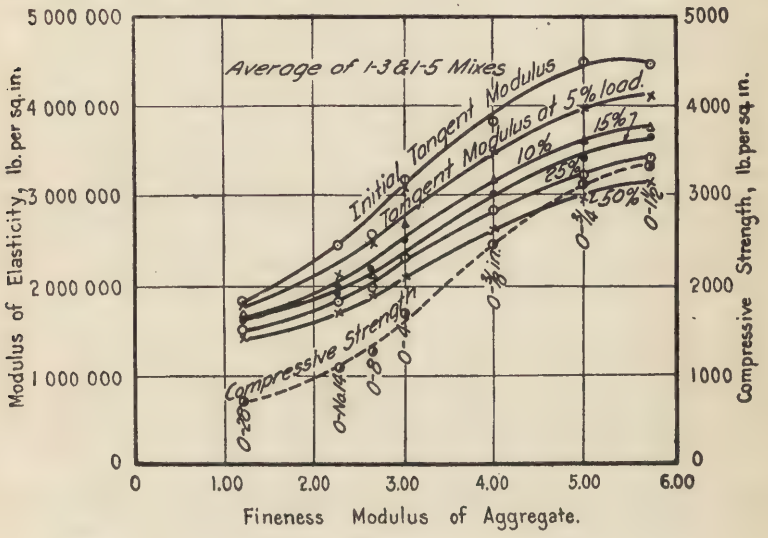


FIG. 15.—Effect of Size of Aggregate on Modulus of Elasticity.

Data from Table 13.
28-day compression tests of 6 by 12-in. cylinders.
Sand and pebble aggregate.
Relative consistency 1.00.
Each value is the average of 10 tests from 2 mixtures.
Compare Fig. 14 and 16.

of the sums of the volumes of mixed aggregate plus cement. For example, in a 1 : 4 mix the quantity of cement is 20 per cent.

Fig. 17 shows the effect of quantity of cement on concrete made with 0–1½-in. aggregate, relative consistency of 1.10, and ages varying from 7 days to 1 year. For the 28-day tests the strength of a 1 : 7 mix is 1400 lb. per sq. in., while for a 1 : 3 mix it is 3000 lb. per sq. in.; or an increase of 111 per cent.

[1]For definite information as to the maximum values of fineness modulus permissible to use for a given mix and maximum size of aggregate, see *Bulletin 1* referred to above.

For the same conditions the moduli of elasticity are 3 400 000 and 4 100 000 lb. per sq. in.; an increase of 21 per cent. The details of the tests are given in Table 7. The values are low, probably due to the fact that the specimens were made in the winter and stored in the basement where the temperature was somewhat low. A similar relation is shown for initial tangent modulus and tangent modulus at 25 per cent of the compressive strength from another series of tests in Fig. 18. Details are given in Table 14.

Tables 8, 9, 10, 12 and 13 give additional tests showing the effect of quantity of cement. These data show that both the modulus of elasticity and strength become greater as the quantity of cement is increased. It will be

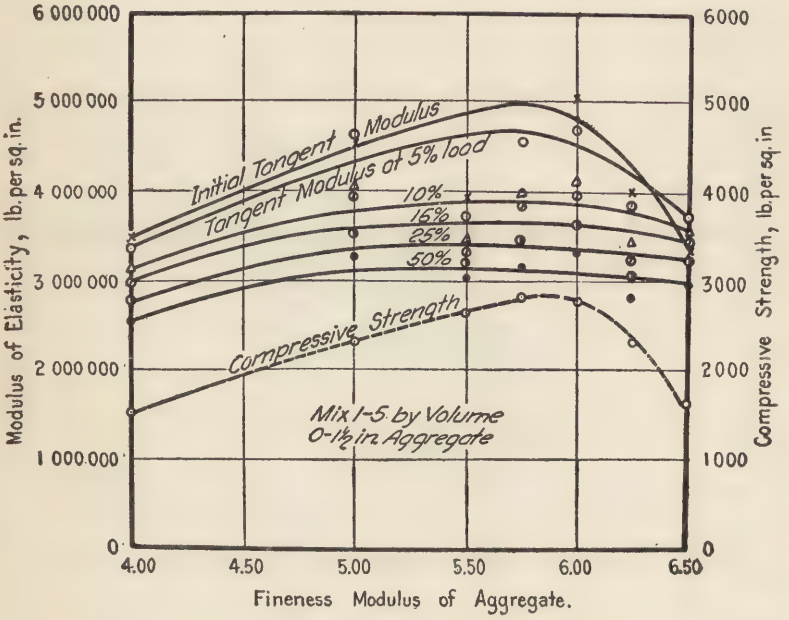


FIG. 16.—Effect of Grading of Aggregate on Modulus of Elasticity.

Data from Table 13, 3rd group.
Compression tests of 6 by 12-in. cylinders.
Sand and pebble aggregate; graded 0–1½ in. Different fineness moduli obtained by variation in proportions of fine and coarse aggregates.
Relative consistency 1.00.
Compare Fig. 14 and 15.

noted that for mixes richer than about 1 : 3 there is a marked falling off in the rate of increase of the modulus of elasticity.

Effect of Consistency.—Fig. 19 and 20 show the effect of quantity of mixing water on the strength and modulus of elasticity of concrete. The abscissas are the relative amounts rather than the actual quantities of water. The details of the tests are given in Tables 4 and 13. Concrete of relative con-

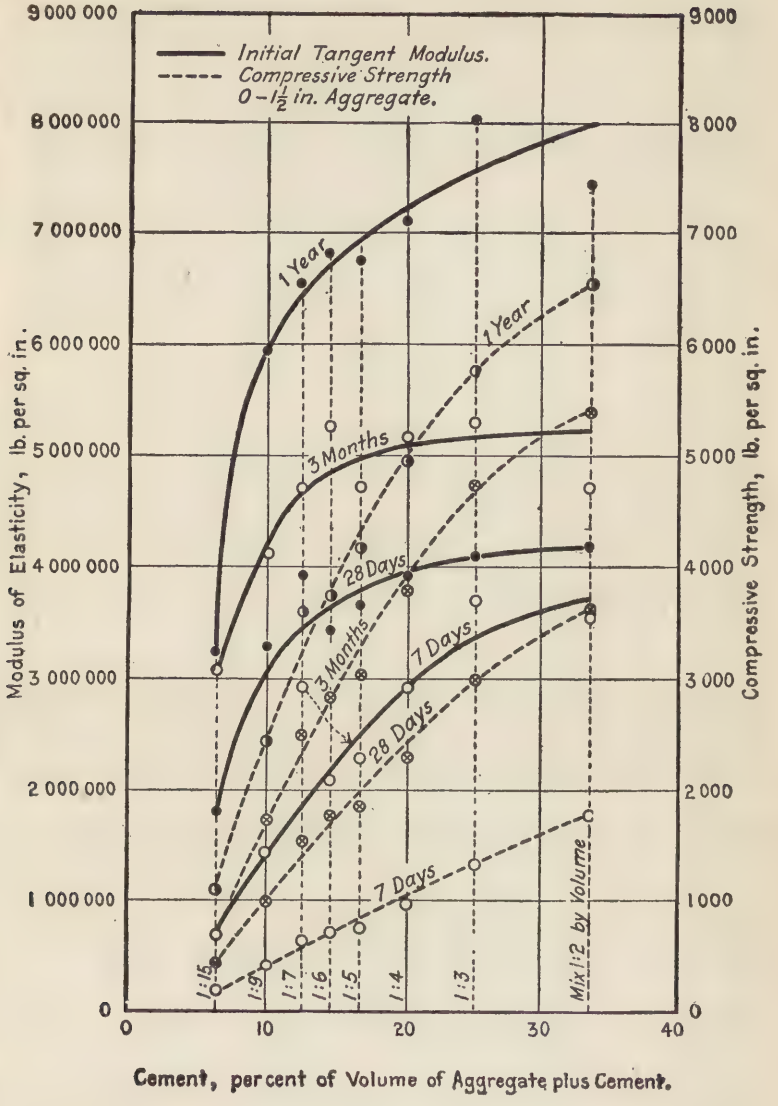


FIG. 17.—Effect of Amount of Cement on Modulus of Elasticity.

Data from Table 7. Machine-mixed concrete.
Compression tests of 6 by 12-in. cylinders.
Sand and pebble aggregate; graded 0–1½ in.
Relative consistency 1.10.
Each value is the average of 24 tests from 6 times of mixing.
Compare Fig. 18.

sistency of 1.00 will slump ½ to 1 in. if the steel form is withdrawn from a freshly molded 6 by 12-in. cylinder, and contains about 20 to 30 per cent less water than used in ordinary reinforced concrete work.

For the 28-day tests in Fig. 19 an addition of 25 per cent of water to the concrete having a relative consistency of 1.00 caused a decrease in strength of about 35 per cent, and a decrease in modulus of elasticity of about 15 per cent. Additional data from another series of tests are given in Fig. 20.

The amount of mixing water used has a most marked effect on the strength and modulus of elasticity of the resulting concrete. These tests as well as many others made in this Laboratory show that the benefits of well-graded aggregates and rich mixes may be minimized or lost by using too much mixing water.

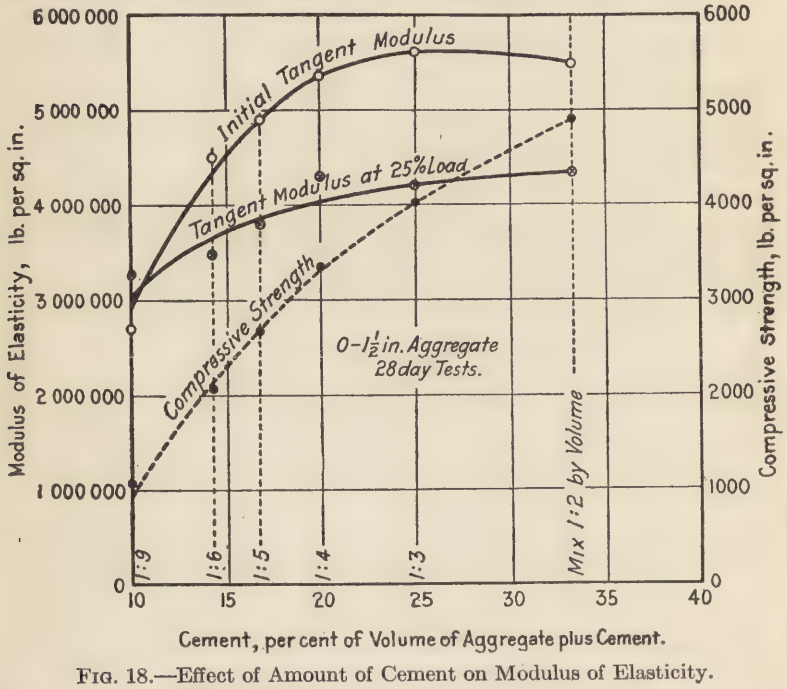


FIG. 18.—Effect of Amount of Cement on Modulus of Elasticity.

Data from Table 14.
28-day compression tests of 6 by 12-in. cylinders.
Sand and pebble aggregate; graded 0–1½ in.
Relative consistency 1.00.
Compare Fig. 17.

It will be noted that abnormally low strengths and moduli are obtained for relative consistencies less than about 0.90 to 1.00. Such consistencies are too dry for proper mixing and molding.

It has been shown by Abrams[1] that the quantity of mixing water expressed as a ratio to the volume of cement dictates the strength of the resulting con-

[1]See "Effect of Time of Mixing on the Strength and Wear of Concrete," by D. A. Abrams, Proc. Am. Concrete Inst., June, 1918; also "Design of Concrete Mixtures," *Bulletin 1*, Structural Materials Research Laboratory.

crete, regardless of the mix, consistency and grading of aggregate, so long as the concrete is plastic.

Effect of Age of Concrete[1].—Fig. 21 and 22 show the increase in modulus of elasticity and strength of concrete with age at test for ages ranging from 7 days to 5 years. The details of the tests are given in Tables 4 and 7.

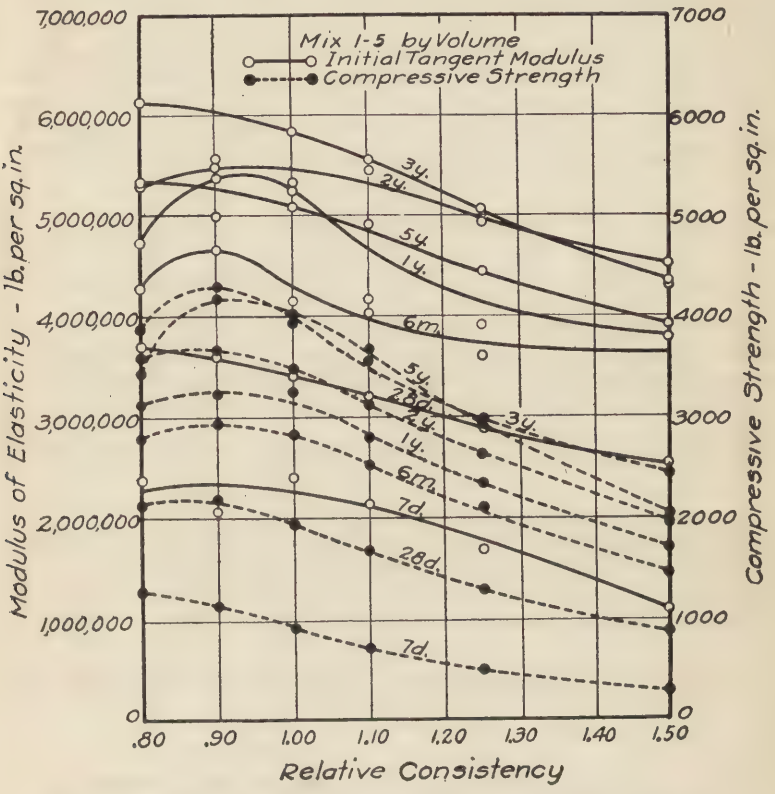


FIG. 19.—Effect of Consistency of Concrete on Modulus of Elasticity.

Data from Table 4.
Compression tests of 6 by 12-in. cylinders.
Each value is the average of 15 tests from 3 sizes of sand and pebble aggregate.
Compare Fig. 20.

Fig. 21 shows the influence of age on modulus of elasticity and strength platted in the form of the usual age-strength curve for data from Table 4. In Fig. 22 data from Table 7 are platted with age to a logarithmic scale. On this diagram it will be noted that the age-strength relation is a straight line, indi-

[1](Note to Revised Edition.) Tests reported in Table 4 and platted in Fig. 21 show the modulus of elasticity at 5 years to be lower than at 3 years. The reason for this discrepancy has not been satisfactorily explained. In general the strength increased for all ages up to 5 years.

cating that the strength is proportional to the logarithm of the age.[1] The age-modulus-of-elasticity relationi s also approximately a straight line. Here, as for the other variables, the modulus of elasticity does not increase as rapidly as the strength. For the 2-in. aggregate the modulus of elasticity at 1 year is 180 per cent of the value at 28 days, while the strength for 1 year is about 230 per cent of that at 28 days.

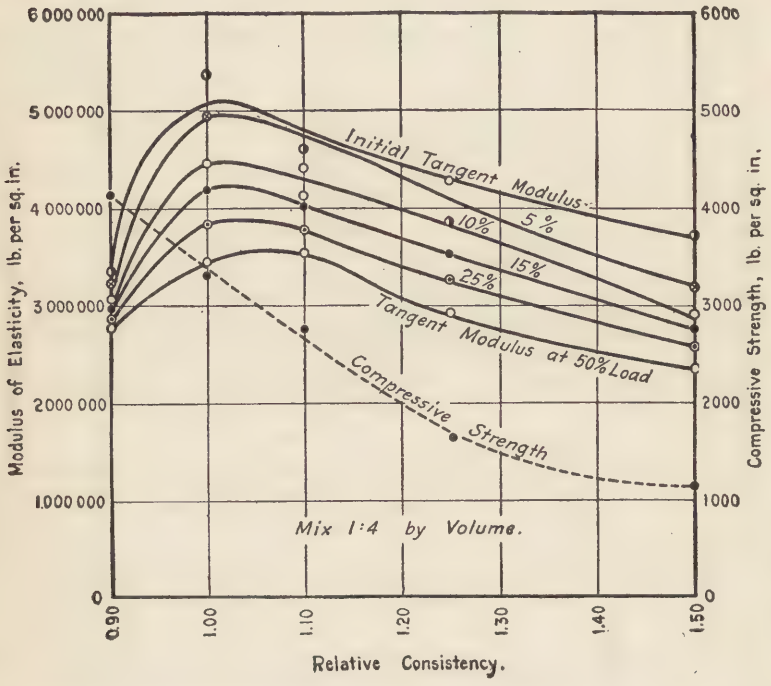


FIG. 20.—Effect of Consistency of Concrete on Modulus of Elasticity.

Data from Table 13.
28-day compression tests of 6 by 12-in. cylinders.
Sand and pebble aggregate; graded 0–1½ in.
Compare Fig. 19.

Effect of Kind of Aggregate.—In Table 10 moduli of elasticity and strengths are given for concrete made from 4 different coarse aggregates: pebbles, crushed limestone, blast furnace slag and granite. All coarse aggregates were similarly graded, the sizes ranging from No. 4 sieve to 1½ in. A high-grade torpedo sand was used as fine aggregate. Parallel tests were made on mixes from 1 : 6 to 1 : 2, of 1.10 consistency, for two conditions of storage: (1) 14 days in damp

[1] See "Effect of Age on the Strength of Concrete," by D. A. Abrams, Proc. Am. Soc. Testing Mat., Part II, p. 317 (1918).

sand and 77 days in air, and (2) 3 months in damp sand. The following table gives average strengths and moduli of elasticity for all mixes and both conditions of storage:

Kind of Aggregate.	Compressive Strength, lb. per. sq. in.	Modulus of Elasticity, lb. per sq. in.	
		Initial Tangent.	Tangent at 25 per cent of Compressive Strength.
Pebbles	3 810	5 400 000	3 860 000
Limestone	3 930	5 940 000	4 210 000
Slag	3 800	5 580 000	4 220 000
Granite	3 970	5 780 000	4 100 000

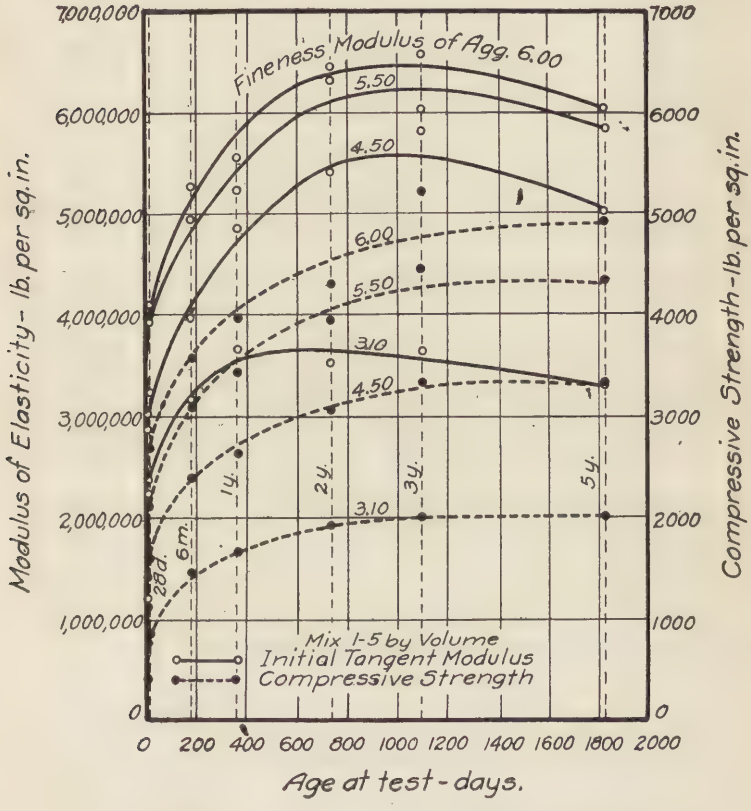


FIG. 21.—Effect of Age of Concrete on Modulus of Elasticity.

Data from Table 4.
Compression tests of 6 by 12-in. cylinders.
Mix 1 : 5 by volume.
Each value is the average of 30 to 35 tests from 6 or 7 consistencies.
Compare Fig. 22.

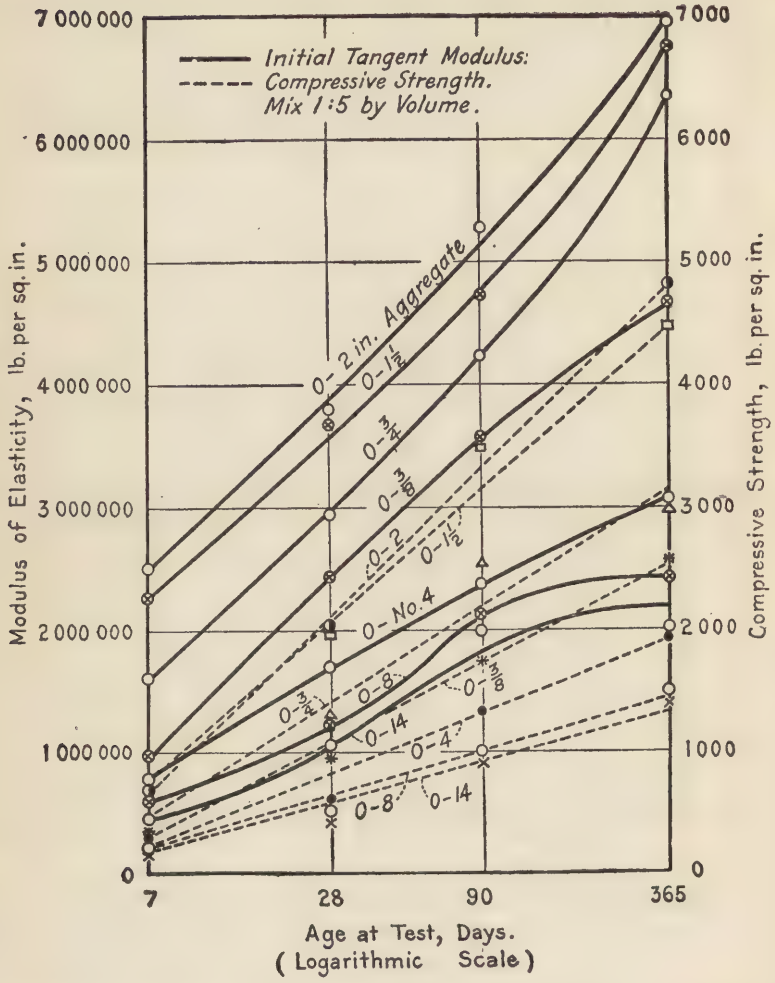


FIG. 22.—Effect of Age of Concrete on Modulus of Elasticity; Age Platted to Logarithmic Scale.

Data from Table 7.
Compression tests of 6 by 12-in. cylinders.
Sand and pebble aggregate.
Relative consistency 1.10.
Each value is the average of 24 tests from 6 or 7 times of mixing.
Compare Fig. 21.

These tests show little variation in either strength or modulus of elasticity of concrete made from the 4 types of coarse aggregates. This result should be contrasted with the published tests on concrete made from different aggregates. These tests undoubtedly show the correct relation. The uniformity in properties is to be expected since the aggregates were graded alike and the water proportioned in such a manner that the varying absorption was taken into account. Many serious errors have been made in discussing tests of this kind due to failure to take into account differences in grading and absorption of aggregate.

Effect of Curing Condition of Concrete.—Table 10 gives tests on 140 6 by 12-in. cylinders, about half of which were stored 3 months in damp sand and the remainder 14 days in damp sand and 77 days in air. A grand average of the strength and modulus of elasticity for each condition of storage shows that the concrete stored the entire time in damp sand gives the higher values. The average compressive strength of air-stored specimens were 3640 lb. per sq. in. and for the sand-stored specimens 4100 lb. per sq. in. The average initial tangent modulus for air-stored specimens was 5 330 000 and for the sand-stored specimens 6 020 000 lb. per sq. in. The tangent modulus at 25 per cent of the compressive strength was 3 650 000 for the air-stored concrete and 4 550 000 lb. per sq. in. for that stored in damp sand.[1]

Effect of Time of Mixing.—Table 6 gives data on the effect of time of mixing on the strength and modulus of elasticity of concrete. The values given in this table are the average of a number of different consistencies, sizes of aggregates, and mixes. The details of the strength tests were reported by Professor Abrams to the American Concrete Institute in 1918.[2]

In general both the modulus of elasticity and strength are greater for the longer mixing times.

Relation between Modulus of Elasticity and Compressive Strength.—The Joint Committee on Standard Specifications for Concrete and Reinforced Concrete[3] recommends that "in computations for the position of the neutral axis for the resisting moment of beams and for compression of concrete in columns" the modulus of elasticity be assumed as:[4]

(1) 1/40 that of steel, when the compressive strength of the concrete at 28 days is below 800 lb. per sq. in.

(2) 1/15 that of steel, when the compressive strength of the concrete at 28 days lies between 800 and 2200 lb. per sq. in.

(3) 1/12 that of steel, when the compressive strength of the concrete at 28 days lies between 2200 and 2900 lb. per sq. in.

(4) 1/10 that of steel, when the compressive strength of the concrete at 28 days is higher than 2900 lb. per sq. in.

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[1] For further information on the effect of curing conditions, see "Effect of Curing Condition on the Wear and Strength of Concrete," by D. A. Abrams, *Bulletin 2*, Structural Materials Research Laboratory.

[2] "Effect of Time of Mixing on the Strength and Wear of Concrete."

[3] Proc. Am. Soc. Testing Mat., Vol. 21, p. 212, 1921.

[4] (Note to Revised Edition.) In revising this Bulletin, the wording of the recommendations of the Joint Committee for modulus of elasticity has been revised from that used in 1917 to conform with the Progress Report of the Joint Committee on Standard Specifications for Concrete and Reinforced Concrete; 1921.

(5) 1/8 that of steel for calculating the deflection of reinforced concrete beams which are free to move longitudinally at the supports, and in which the tensile resistance of the concrete is neglected.

A study of these recommendations leads one to the conclusion that they are based on the assumption that the ratio of modulus of elasticity to the compressive strength of concrete is about 1000.

Taylor and Thompson[1] state that while there is probably some relation between strength and modulus of elasticity, it is so complex that it will probably never be discovered. They give 1300 as the approximate ratio of modulus of elasticity to strength.

Falk[2] concludes that the modulus of elasticity as determined by compression tests is 1325 times the ultimate strength of the concrete.

Thacher[3] gives the following formulas derived from Kimball's tests for concrete of different ages, which do not take into account directly the compressive strength:

THACHER'S FORMULAS FOR MODULUS OF ELASTICITY.

7 days old.....$E = 2\,600\,000 - 700\,000\left(\frac{\text{volume of sand}}{\text{volume of cement}} - 2\right)$.
1 month old.....$E = 2\,900\,000 - 300\,000$ (" -1).
3 months old.....$E = 3\,600\,000 - 500\,000$ (" -2).
6 months old.....$E = 3\,600\,000 - 600\,000$ (" -3).

If the term $\left(\frac{\text{volume of sand}}{\text{volume of cement}} - c\right)$ is zero or becomes a negative quality, the entire term is to be considered zero.

All of the above relations with the exception of Thacher's assume a constant ratio between the modulus of elasticity and strength. Thacher's formulas are of limited application since they do not take into account such important variables as the grading of the aggregate and the consistency of concrete.

Schüle[4] derives an equation for the "relation between modulus of elasticity of concrete (in tons per sq. cm.) and its crushing strength (kg. per sq. cm.)" as follows:

$$E_b = \frac{B^2 - 25.16B + 50.38}{0.001646B^2 + 0.224B + 7.65}$$

in which E_b = modulus of elasticity of concrete, tons per sq. cm. and B = ultimate compressive strength, kg. per sq. cm.
In units of pounds per square inch this equation may be written,

$$E_b = \frac{70B^2 - 25\,100B + 717\,000}{0.000008B^2 + 0.0157B + 7.65}$$

While this equation, in our opinion, more nearly represents the true form of the relation than any of those quoted from other writers, it is open to the objection that negative values for E_b are obtained for values of B less than 22.96 kg. per sq. cm. (330 lb. per sq. in.)

[1] Taylor and Thompson, "Concrete, Plain and Reinforced."
[2] Falk, "Cements, Mortars and Concretes."
[3] "Concrete and Reinforced Concrete Construction," by Reid.
[4] Proc. Sixth Congress, Inter. Assoc. Testing Mat., New York, 1912, Second Section.

Our tests show that the relation between modulus of elasticity and strength for mixes ranging from 1 : 15 to about 1 : 3 may be represented by a single curve, but the relation is not linear. Ratios ranging from about 4000 for the low strengths to 1000 for the high strengths were found.

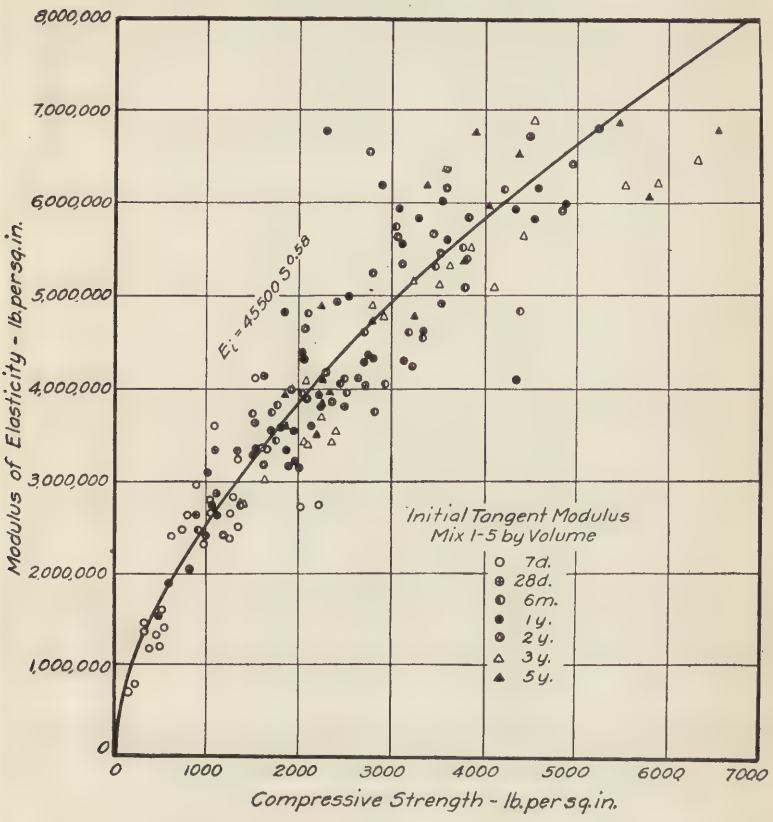


FIG. 23.—Relation of Modulus of Elasticity to Strength of Concrete.

Data from Table 4.
Compression tests of 6 by 12-in. cylinders.
Sand, pebble and crushed limestone aggregate.
In general, each value is the average of 5 tests made on different days.
Compare Fig. 24 to 33 inclusive.

The relation between modulus of elasticity and strength of concrete from tests covered in this report may be represented by the equation,

$$E = CS^m \quad \ldots\ldots\ldots\

For the different series of tests, the constants vary over a considerable range. However, in cases where C is larger than the average, m is smaller, and therefore for ordinary ranges in strength the values of modulus of elasticity given by the equations from the different series of tests show a good agreement.

Fig. 23 shows the relation for initial tangent modulus to compressive strength for concrete made from 4 different sizes of pebble aggregate and one

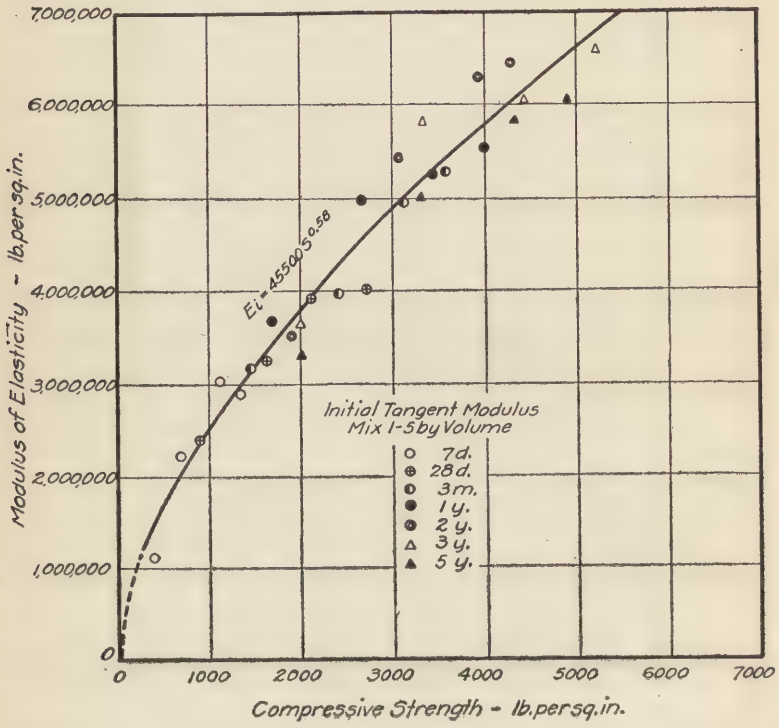


FIG. 24.—Relation of Modulus of Elasticity to Strength of Concrete.

Data from Table 4.
Compression tests of 6 by 12-in. cylinders.
Sand, pebble and crushed limestone aggregate.
Same data as in Fig. 23, except that each value is the average of 30 to 35 tests from each of the 6 or 7 consistencies.
Compare Fig. 23 and 25 to 33 inclusive.

size of limestone aggregate, for consistencies ranging from very dry to sloppy mixes, and for ages ranging from 7 days to 5 years. The curve in this figure may be represented by the equation,

$$E_i = 45\,500\,S^{0.58} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

The points on this diagram are more scattered than in others, for three causes:

1. Each value is the average of 5 or fewer tests, whereas in most of the other diagrams each value is based on 10 to 80 tests. Our experience has shown that moduli of elasticity should be the averages of 10 or more tests to give concordant results.

2. Readings for tests earlier than 1 year were taken with the Johnson wire-wound dial, which does not give as uniform results as the Ames instrument.

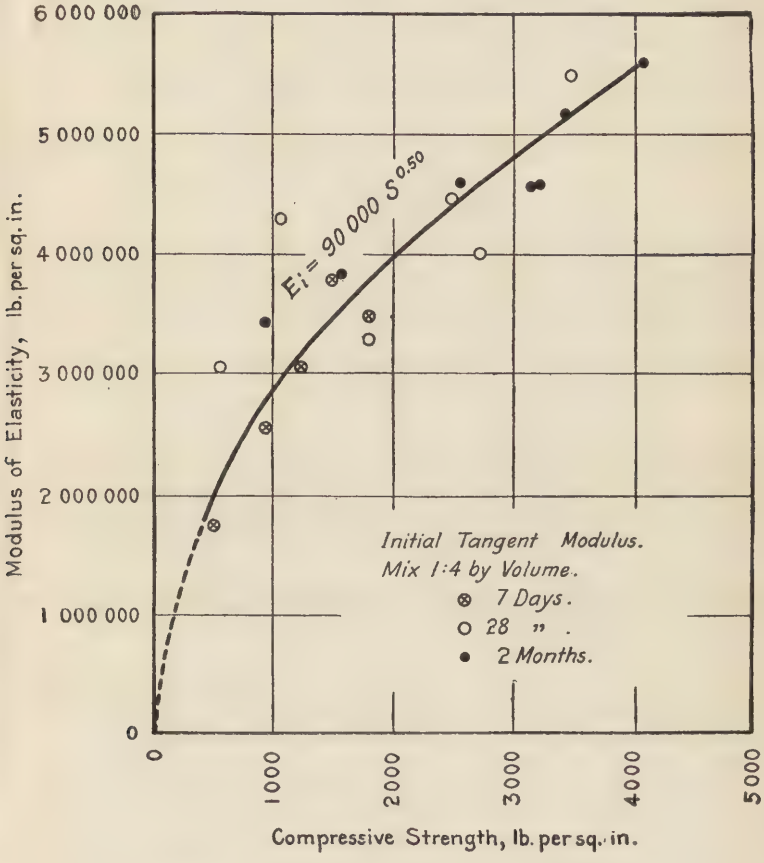


FIG. 25.—Relation of Modulus of Elasticity to Strength of Concrete.

Data from Table 5.
Machine-mixed concrete.
Compression tests of 6 by 12-in. cylinders.
Sand and pebble aggregate; graded 0–1½ in.
Each value is the average of 24 tests from 6 times of mixing.
Compare Fig. 23, 24 and 26 to 33 inclusive.

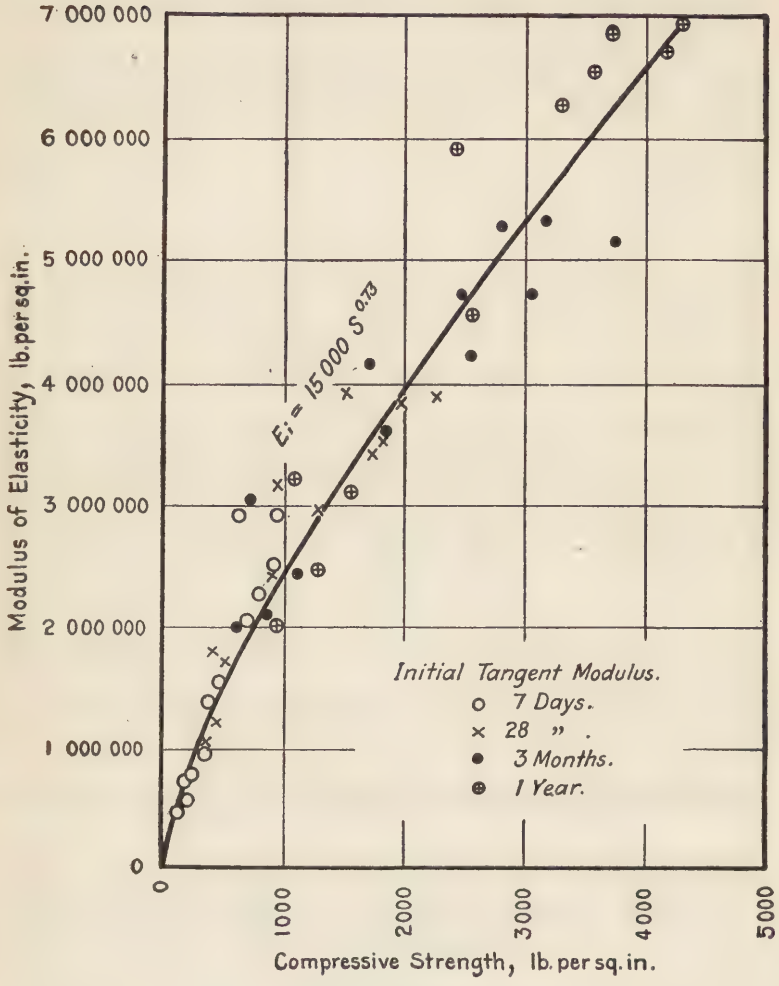


FIG. 26.—Relation of Modulus of Elasticity to Strength of Concrete.

Data from Table 7.
Machine-mixed concrete.
Compression tests of 6 by 12-in. cylinders.
Sand and pebble aggregate.
Relative consistency 1.10.
Each value is the average of 24 tests from 6 times of mixing.
Compare Fig. 23 to 25 and 27 to 33 inclusive.

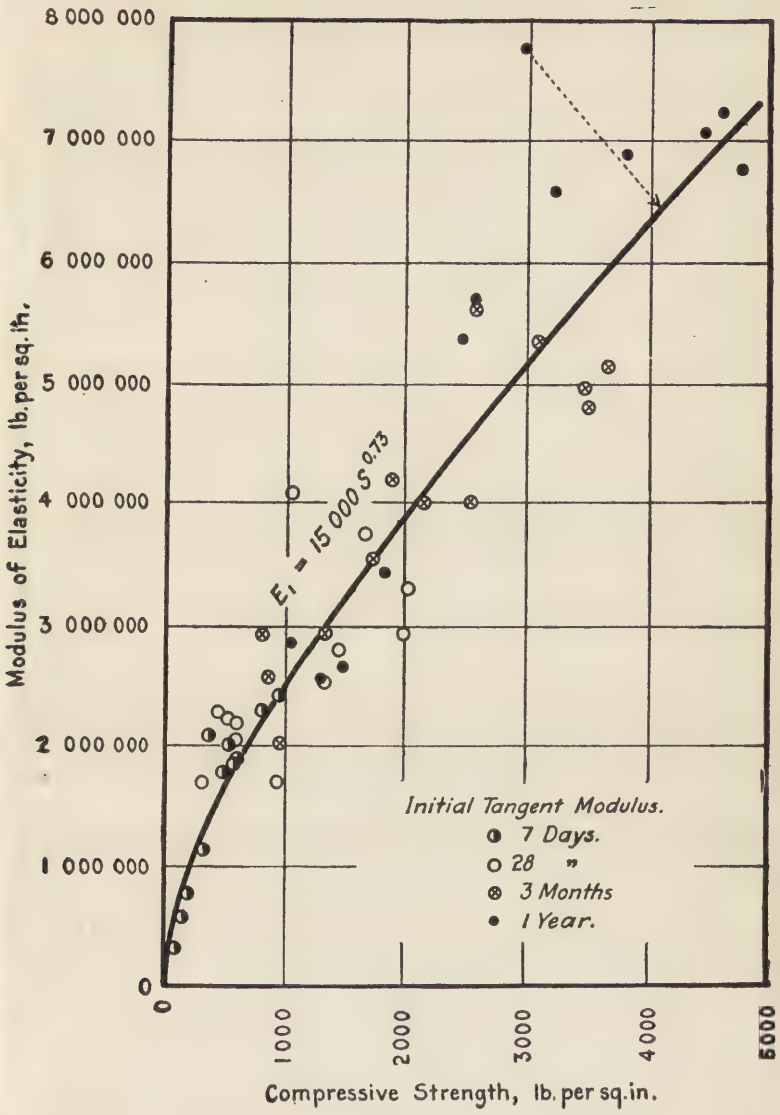


FIG. 27.—Relation of Modulus of Elasticity to Strength of Concrete.

Data from Table 8.
Hand mixed concrete.
Compression tests of 6 by 12-in. cylinders.
Sand and pebble aggregate.
Relative consistency 1.10.
Each value is the average of 4 tests made on different days.
Compare Fig. 23 to 26 and 28 to 33 inclusive.

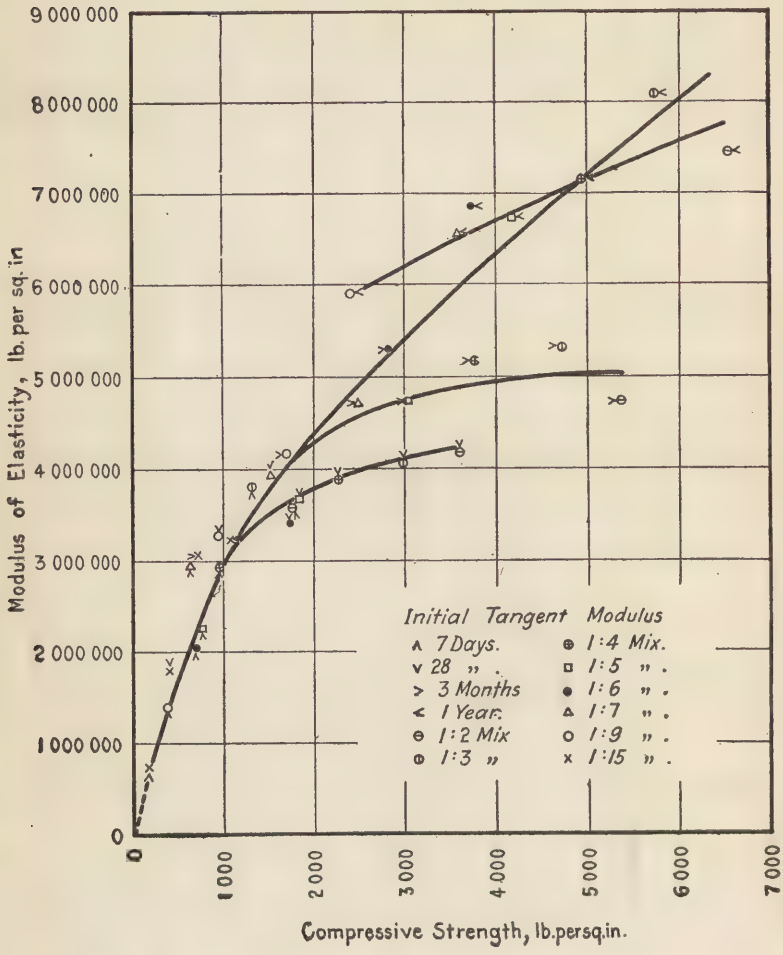


FIG. 28.—Relation of Modulus of Elasticity to Strength of Concrete.

Data from Table 7.
Compression tests of 6 by 12-in. cylinders.
Sand and pebble aggregate; graded 0–1½ in.
Relative consistency 1.10.
Each value is the average of 24 tests from 6 times of mixing.
Compare Fig. 23 to 27 and 29 to 33 inclusive.

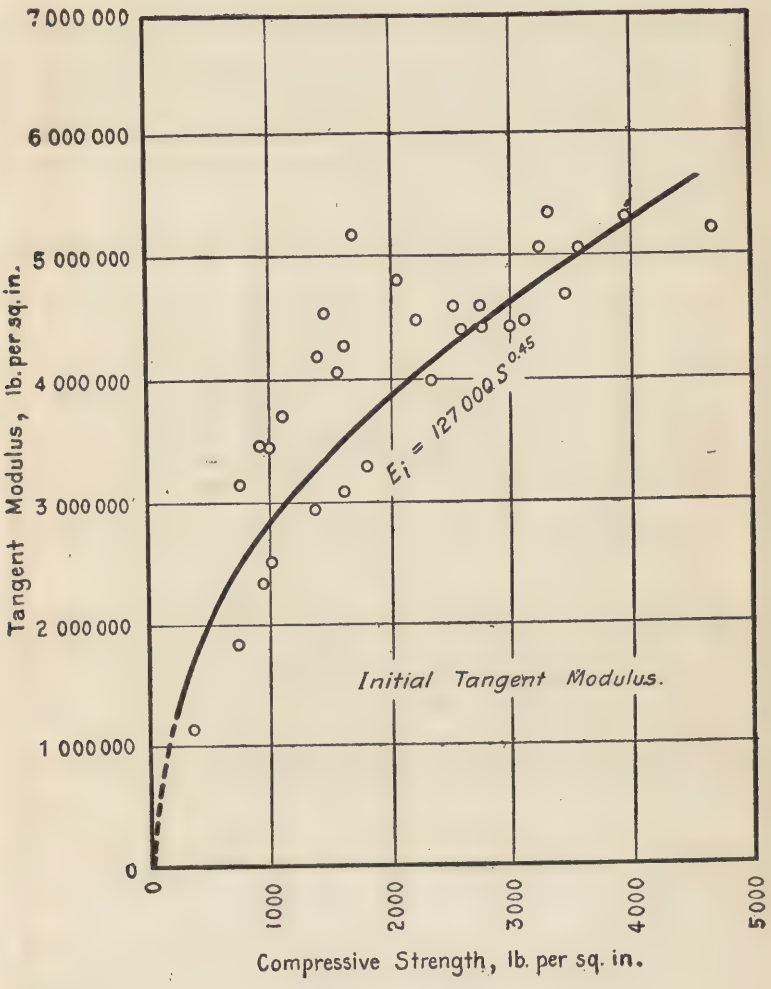


FIG. 29.—Relation of Modulus of Elasticity to Strength of Concrete.

Data from Table 13.
28-day compression tests of 6 by 12-in. cylinders.
Sand and pebble aggregate.
Each value is the average of 5 tests made on different days.
Compare Fig. 23 to 28 and 30 to 33 inclusive.

3. Some of the mixtures (those represented by relative consistencies less than 0.90) were too dry to make a plastic concrete and hence gave erratic results.

The data from Fig. 23 are shown in Fig. 24 except that the average of all the consistencies in each group is platted instead of individual values. An equation having the same constants is found. The curve is more uniform because each value is the average of about 30 tests instead of 5. This diagram brings out pointedly the fact that the relation between strength and modulus of elasticity for ages ranging from 7 days to 5 years can be represented by the same curve.

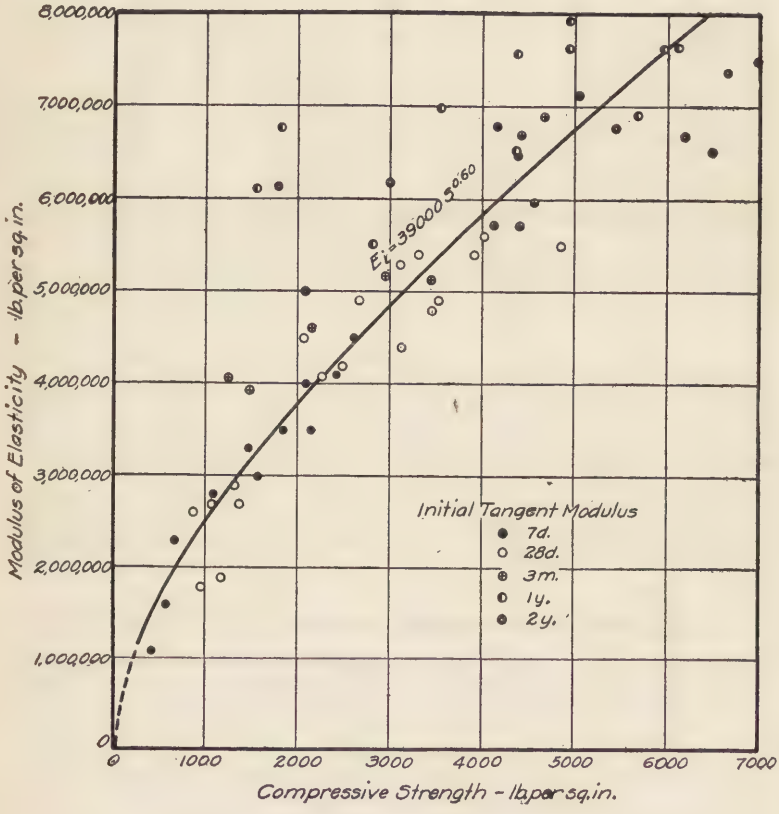


FIG. 30.—Relation of Modulus of Elasticity to Strength of Concrete.

Data from Table 14.
Compression tests of 6 by 12-in. cylinders.
Sand and pebble aggregate.
Compare Fig. 23 to 29 and 31 to 33 inclusive.

Fig. 25 gives a similar relation for another series of tests. The concrete represented by this figure was machine mixed. The mix was 1 : 4, using 0–1½-in. pebble aggregate and consistencies ranging from very dry to sloppy. Tests were made at ages of 7 and 28 days and 2 months. For these data the relation between strength and modulus of elasticity is expressed by the equation,

$$E_i = 90\,000\,S^{0.50} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

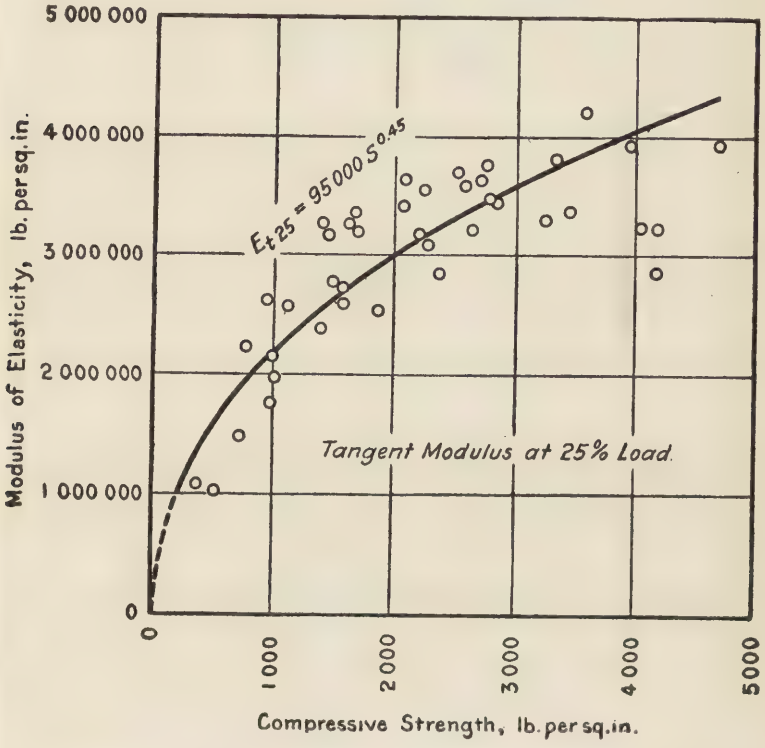


FIG. 31.—Relation of Modulus of Elasticity to Strength of Concrete.

Data from Table 13.
28-day compression tests of 6 by 12-in. cylinders.
Sand and pebble aggregate.
Compare Fig. 23 to 30 inclusive, 32 and 33.

These constants are considerably different from those in the two preceding figures, but a comparison of the curves over the ordinary range will show that there is no great difference in the modulus of elasticity for a given strength. For example, in Fig. 25 for a concrete having an ultimate strength of 1000 lb. per sq. in. the average curve gives a modulus of elasticity of 2 800 000 lb. per

sq. in., while for the two preceding curves the average is 2 500 000 lb. per sq. in. For 2000-lb. concrete the discrepancy is still less, the values obtained being 4 000 000 and 3 800 000 lb. per sq. in. respectively.

Fig. 26 and 27 give the data from Tables 7 and 8. The mixtures ranged from 1 : 15 to 1 : 4, the consistency was 1.10, and the aggregate ranged in size from 0–No. 28 sand to 0–2-in. gravel. Data in Table 7 are the average of 6 times of machine-mixing ranging from ¼ to 10 minutes. Values are given

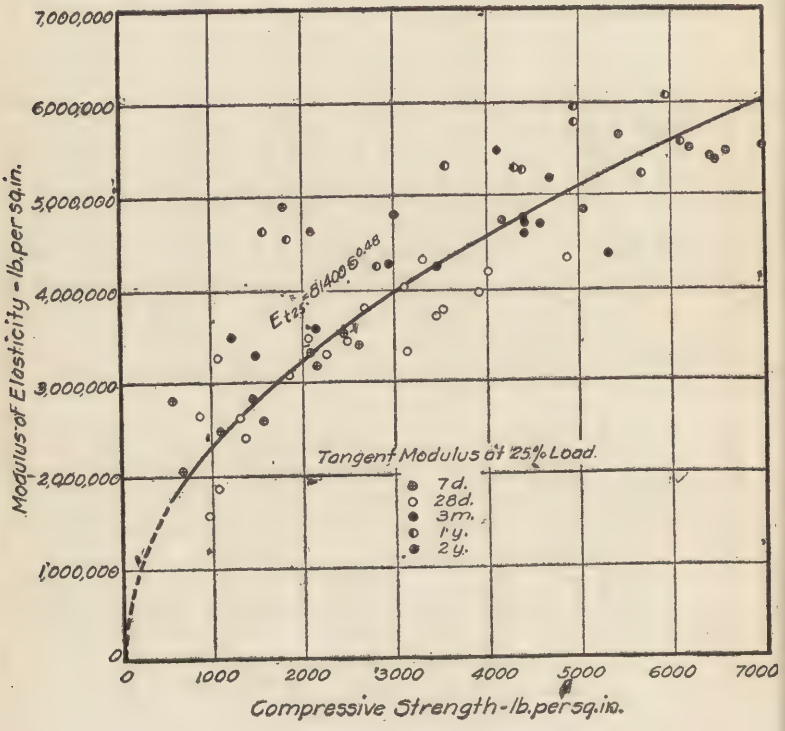


FIG. 32.—Relation of Modulus of Elasticity to Strength of Concrete.

Data from Table 14.
Compression tests of 6 by 12-in. cylinders.
Sand and pebble aggregate.
Compare Fig. 23 to 31 inclusive, and 33.

in Table 8 for hand-mixed concrete of the same composition. The constants for these equations are the same; in other words, there is no difference between machine-mixed and hand-mixed concrete so far as the relation of modulus of elasticity to strength is concerned. It will be noted that there is considerable difference between the constants for these curves and those given in Fig. 23

to 25. However, a direct comparison will show that the differences in moduli of elasticity for concrete of given strengths are not as great as the difference in constants might at first seem to indicate. In Fig. 26 and 23 the moduli of elasticity for 1000 and 2000-lb. concrete are almost the same. It is for the higher strengths that the differences are more pronounced. In Fig. 26, 4000-lb. concrete gives a modulus of elasticity of 6 600 000 lb. per sq. in., while Fig. 23 gives 5 700 000 lb. per sq. in.

Fig. 28 gives data from Group 1 of Table 7 for mixtures ranging from 1 : 15 to 1 : 2 and ages ranging from 7 days to 1 year. The aggregates were of the same size, being graded up to 1½ in. The consistency was such as might be used in ordinary concrete road mixtures. The richer mixes show a falling-off from the average curve. Reference to Fig. 17 emphasizes this point. This indicates that the general relation given in Eq. 8 does not hold for mixes richer than about 1 : 3.

Fig. 29 and 30 show the relation between modulus of elasticity and strength for data from Tables 13 and 14. In Fig. 29 mixes richer than 1 : 3 were omitted. For these tests values of modulus of elasticity were calculated at various percentages of load. Fig. 31 and 32 show this relation for the tangent modulus at 25 per cent of the compressive strength. These curves follow the same general law as those for initial tangent modulus, but give results about 15 to 25 per cent lower.

In Table 16 the average values for initial tangent modulus and tangent modulus at 25 per cent of the compressive strength taken from Fig. 23 to 32 inclusive are tabulated. As pointed out above, while the constants of these equations vary over a considerable range the values of modulus of elasticity obtained are not greatly different. The grand average of all tests in this table may be represented by the following equations:

$$E_i = 40\,000\,S^{0.60} \quad \ldots\ldots (11)$$

$$E_{t25} = 84\,300\,S^{0.47} \quad \ldots\ldots (12)$$

Without appreciable error they may be written:

$$E_i = 33\,000\,S^{\frac{2}{3}} \quad \ldots\ldots (13)$$

$$E_{t25} = 66\,000\,S^{\frac{1}{2}} \quad \ldots\ldots (14)$$

It may be of interest to note that Eq. 11 is based on about 2500 tests of 6 by 12-in. cylinders and Eq. 12 on about 800 tests.

The following table shows a comparison of moduli of elasticity obtained from Eq. 11 and equations given by other writers:

Compressive Strength, lb. per sq. in.	Modulus of Elasticity, lb. per sq. in., from				
	Eq. 11.	Schüle's Equation.	Taylor and Thompson's Ratio.	Falk's Ratio.	Joint Committee's Ratio.
1000	2 520 000	1 430 000	1 300 000	1 325 000	1 000 000
1500	3 170 000	2 430 000	1 950 000	1 990 000	1 500 000
2000	3 820 000	3 360 000	2 600 000	2 650 000	2 000 000
2500	4 440 000	3 850 000	3 250 000	3 320 000	2 500 000
3000	4 800 000	4 400 000	3 900 000	3 980 000	3 000 000
4000	5 900 000	5 110 000	5 200 000	5 300 000	4 000 000
5000	6 660 000	5 640 000	6 500 000	6 630 000	5 000 000

Fig. 33 shows data from Table 4 with the modulus of elasticity expressed as a ratio to the compressive strength of the concrete. This ratio varies from about 4100 for 200-lb. concrete to about 1200 for 5000-lb. concrete.

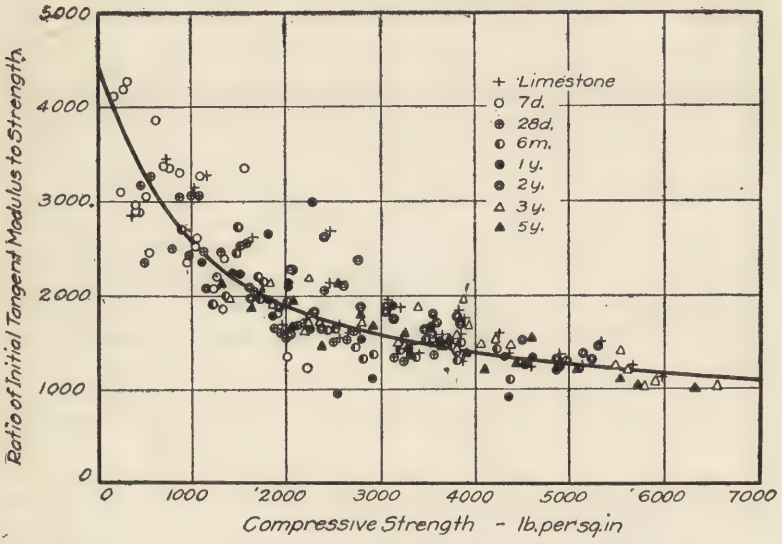


FIG. 33.—Relation of Modulus of Elasticity to Strength of Concrete.

Data from Table 4.
Compression tests of 6 by 12-in. cylinders.
Sand, pebble and crushed limestone aggregate.
Compare Fig. 23 to 32 inclusive.

MODULUS OF ELASTICITY OF CONCRETE AT DIFFERENT PERCENTAGES OF THE COMPRESSIVE STRENGTH.

The strength-modulus-of-elasticity relation has been shown only for the initial tangent and tangent modulus at 25 per cent of the compressive strength. Obviously tangent and secant moduli for all percentages of the load could not

be presented. The values for initial tangent modulus were given prominence because of their general use. The tangent modulus at 25 per cent of the compressive strength was selected as being representative. In order that complete information may be had for all measures of modulus of elasticity their inter-relation is shown.

In Fig. 34 the tangent moduli at the different percentages of the compressive strength are platted against the initial tangent moduli for the data

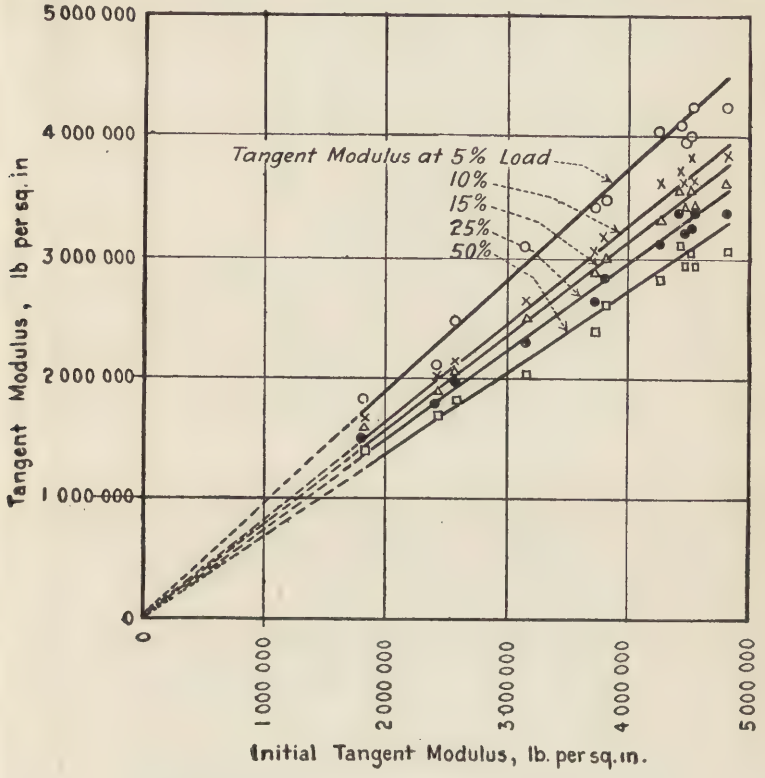


FIG. 34.—Relation of "Initial Tangent" to "Tangent" Modulus.

Data from Table 13.
28-day compression tests of 6 by 12-in. cylinders.
Each value is the average of 40 tests from 8 mixtures.
Compare Fig. 35.

given in Table 13. The average of all the consistencies are platted for each mix. A straight line is obtained showing this relation to be of the form,

$$E_t = b_1 E_i \quad \ldots\ldots\ldots\

For the same data the ratio of tangent modulus to secant modulus is 0.90 (average value of n). Therefore the following equation may be written:

$$E_s = b_2 E_i \quad \ldots\ldots (16)$$

where $b_2 = \frac{b_1}{0.9}$.

Fig. 35 shows the tangent and secant moduli at different percentages of the compressive strength expressed as a ratio to the initial tangent modulus (values of b_1 and b_2).

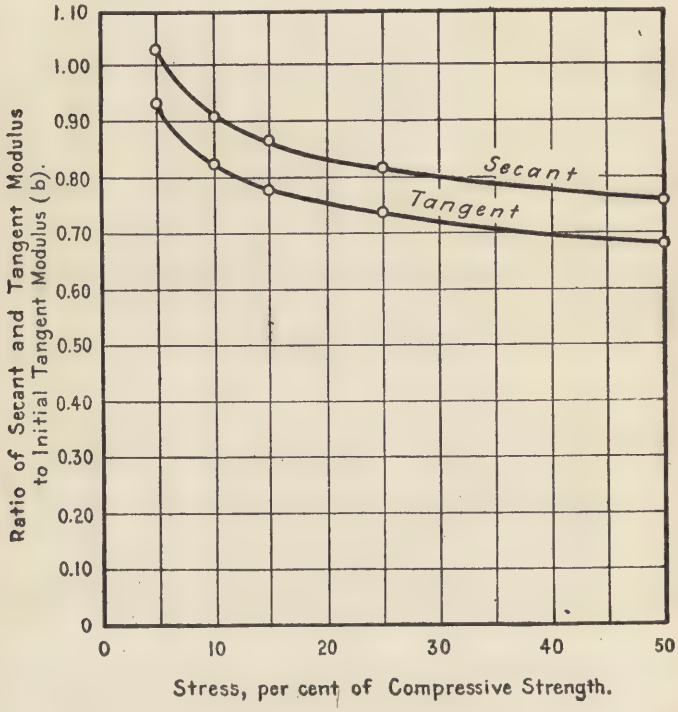


FIG. 35.—Ratio of "Initial Tangent" to "Tangent" and "Secant" Moduli at Different Percentages of the Load.

Data from Table 13.

It was stated above that the initial tangent modulus is equal to the secant modulus at about 5 to 15 per cent of the compressive strength. Reference to Fig. 35 will show that the line marked Secant crosses the 100-per-cent line at about 5 per cent of the compressive strength. In other words, the initial tangent modulus is equal to the secant modulus at this point. Data in Table 12 show the initial tangent modulus to be equal to the secant modulus at about 10 to 15 per cent of the load.

Fig. 36 shows the tangent modulus of elasticity platted against percentage of ultimate strength for the tests given in Table 12. The ratios of the different measures of modulus of elasticity to each other for other data herein reported differ somewhat from those obtained from Fig. 34 to 36, but the general relation is the same.

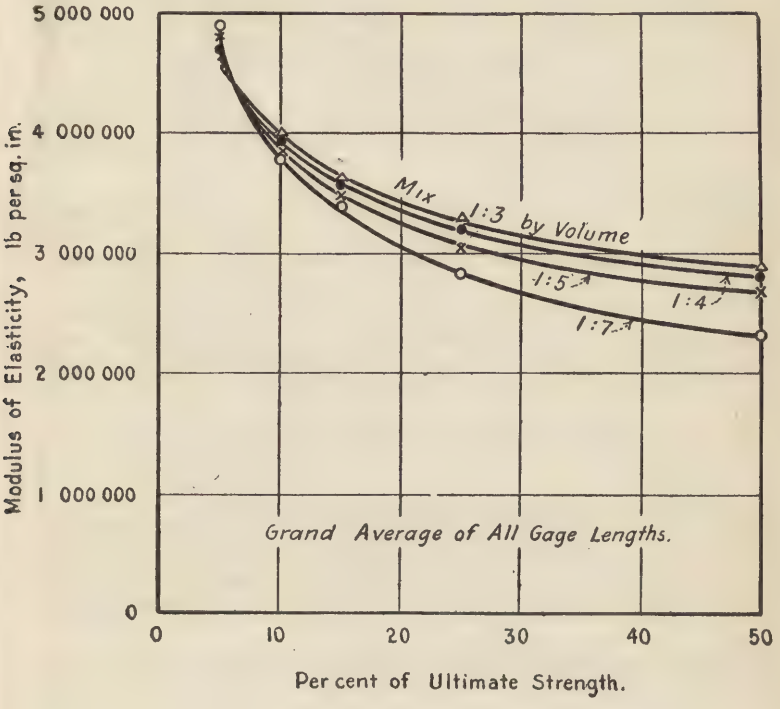


FIG. 36.—Variation of Modulus of Elasticity with Stress at which it is Measured.

Data from Table 12.
28-day compression tests of 6 by 12-in. cylinders.
Sand and pebble aggregate; graded 0–1½ in.
Relative consistency 1.00.
Each value is the average of 80 tests made on 20 days.

NOMOGRAPHIC CHART SHOWING THE INTER-RELATION OF STRENGTH, MODULUS OF ELASTICITY AND COMPOSITION OF CONCRETE.

From the inter-relation of mix, grading, strength, consistency, and the various measures of modulus of elasticity, a nomographic chart on which these variables are represented was constructed (Fig. 37). The data from

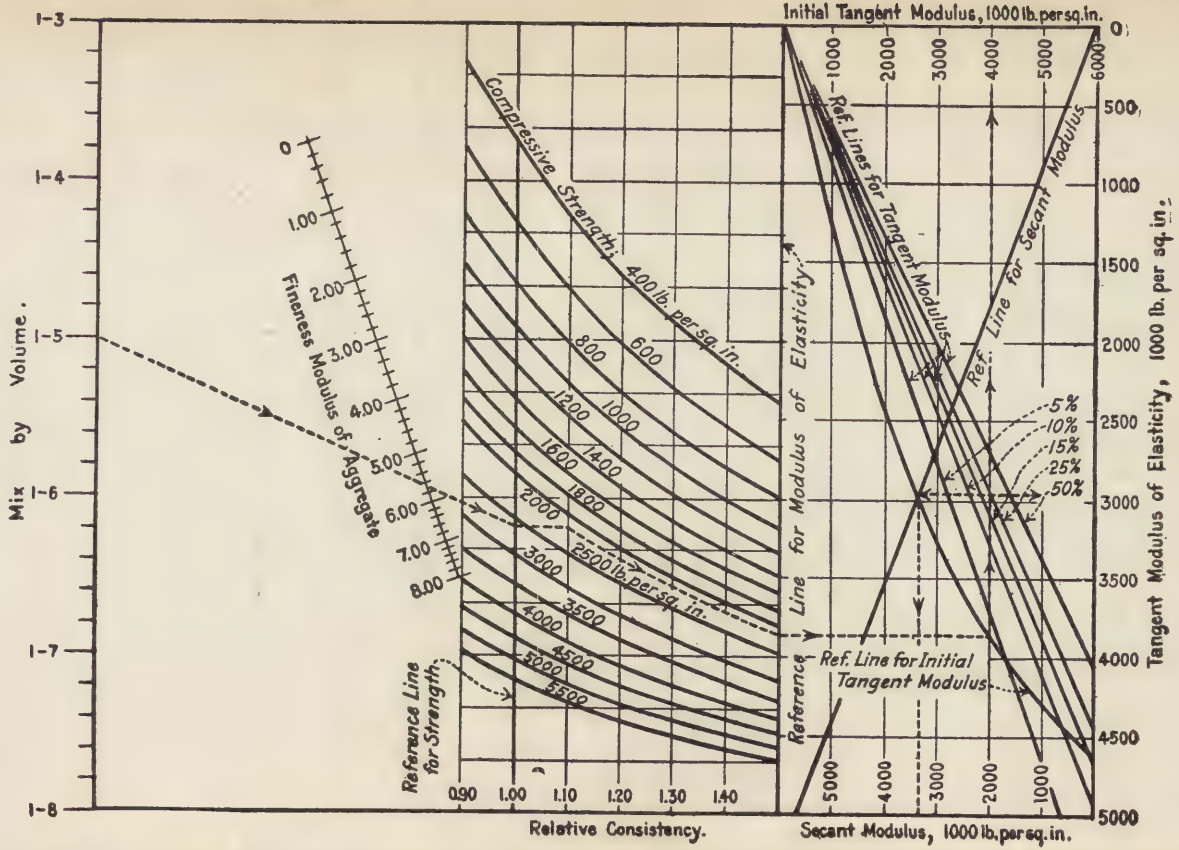


FIG. 37.—Nomographic Chart Showing the Inter-relation of Proportions, Strength and Modulus of Elasticity.

Data from Table 13.
Based on 28-day compression tests of 6 by 12-in. cylinders.
Sand and pebble aggregate.
The portion of the diagram to the left of "Reference Line for Modulus of Elasticity" is similar to Fig. 6 in *Bulletin* 1.

Table 13 were selected as the basis of the chart, since it is for this series only that all of the following variables are represented:

1. Amount of cement (mix);
2. Size and grading of aggregate (fineness modulus);
3. Amount of mixing water (consistency);
4. Compressive strength at 28 days;
5. Initial tangent modulus;
6. Tangent modulus at 5 to 50 per cent of the ultimate load;
7. Secant modulus at 5 to 50 per cent of the ultimate load.

If items 1, 2 and 3 are known, we are able to solve for items 4, 5, 6 and 7. If any one of the four items, 4, 5, 6 and 7, is known the other three can be computed. In using this chart it should be borne in mind that it is based on one series of tests for which the concrete was mixed and cured under laboratory conditions. While it is realized that for a given mix, grading, and consistency, the strengths obtained in practice will be different, it is believed that the relation of modulus of elasticity to strength will be approximately the same as given by the diagram.

Example of Use of Nomographic Chart.—Assume a mix of 1 : 5; 0–1½-in. aggregate, having a fineness modulus of 5.75; relative consistency 1.10.

1. Draw a straight line through the points representing the mix and the grading of the aggregate to the reference line for strength.

2. From this point draw a horizontal line to the line representing 1.10 relative consistency. This intersection gives the compressive strength at 28 days (2200 lb. per sq. in.).

3. Follow the strength contour to the reference line for modulus of elasticity.

4. Draw a horizontal line to the reference line for initial tangent modulus. Vertically above this the initial tangent modulus (4 000 000 lb. per sq. in.) can be read.

5. To obtain the tangent modulus at, say, 25 per cent of the compressive strength, draw a vertical line from the point on the initial tangent curve to the reference line for tangent modulus marked 25 per cent. The tangent modulus (2 900 000 lb. per sq. in.) is then read on the ordinate at the right.

6. If the secant modulus at 25 per cent load is desired, draw a horizontal line from the point on the 25-per-cent tangent modulus line until it intersects the reference lines for secant modulus. The secant modulus (3 300 000 lb. per sq. in.) is read on the bottom scale.

FURTHER DISCUSSION OF STRESS-DEFORMATION RELATION.

For the data used in the construction of the nomographic chart described above it was shown that the average value of n in Eq. 1 is 0.90. If the compressive strength is assumed and the corresponding secant modulus (E_s) is determined from the nomographic chart (Fig. 37), d can be calculated from Eq. 6. Then by substitution in Eq. 1, K can be computed. In like manner, K can be computed for any compressive strength. The relation of K to

compressive strength obtained in this way may be expressed by the equation,

$$K = 29\,000\,S^{\frac{1}{2}} \quad \ldots\ldots\ldots\

from a practically straight line relation between stress and strain is first perceived is designated the *yield point.*"

In the true sense of the word there is no elastic limit for concrete. There is no basis for determining what may be called the elastic limit or "yield point." The method of determination by repeated loading is much too cumbersome for the ordinary tests.

Our tests show that the stress-deformation relation for concrete follows a definite law up to a certain point. Investigation of data from various sources shows this law to apply to numerous materials. The stress-deformation relation of a perfectly elastic body within the elastic limit is of the same form as that given for concrete and other materials, represented by Eq. 1. For a perfectly elastic material n would equal 1, and K would be the modulus of elasticity. It will be seen at once that the point where this law no longer holds is the elastic limit as defined in the usual manner.

For materials that are not perfectly elastic the above law differs only in that n is not equal to 1 (less than 1 for most materials) and that K is the secant modulus at a unit deformation of 1.

As in the case of the perfectly elastic material there is a point beyond which this law no longer holds. It would, therefore, seem that this equation furnishes a method for a determination for all materials of what may be called the "yield point." As has been stated it was not our general custom to take measurements at sufficiently small intervals for loads high enough to determine this point for our tests. In a few instances, however, readings were taken at short intervals for the higher loads and the points beyond which the stress-deformation curve of concrete no longer follows the law expressed in Eq. 1 determined. These are the "yield points" as defined above. The values varied from 50 to 90 per cent of the ultimate load.

CONCLUSIONS.

The modulus of elasticity of any material is the ratio of an increment of stress to a corresponding increment of deformation. The stress-deformation relation of concrete is represented by a curve and, consequently, the modulus of elasticity varies, depending on the point on the curve at which it is measured, becoming less for the higher stresses.

Data for 3 measures of modulus of elasticity are presented as follows:

"Initial tangent" modulus (E_i);

"Tangent" modulus at stresses ranging from 5 to 50 per cent of the compressive strength (E_t);

"Secant" modulus to stresses 5 to 50 per cent of the compressive strength (E_s).

The initial tangent modulus and the tangent modulus at 25 per cent of the compressive strength are treated in detail. The values for initial tangent modulus were given prominence because of their general use. Obviously the relation for all values of secant and tangent modulus could not

be shown. The tangent modulus at 25 per cent of the compressive strength was selected as representative. The inter-relation of the various measures is shown.

A study of the data contained in this report seems to warrant the following conclusions:

1. The relation of compressive stress to deformation for concrete may be represented by the equation:

$$s = Kd^n \quad \ldots\ldots (1)$$

where s = unit stress of concrete, d = unit deformation of concrete, K = a constant which depends on the strength of the concrete, n = an exponent, approximately constant. The curve represented by this equation has a decreasing slope, and gives decreasing values of modulus of elasticity as the stress is increased.

2. The modulus of elasticity of the concrete is a function of the compressive strength. The relation between modulus of elasticity and strength for mixtures leaner than about 1 : 3 may be represented by an equation of the form,

$$E = CS^m \quad \ldots\ldots (8)$$

where E = modulus of elasticity of concrete, C = a constant depending on the conditions of the tests, S = compressive strength of concrete, m = an exponent.

For the initial tangent modulus the average of our tests may be expressed by the equation,

$$E_i = 33\,000\, S^{\frac{5}{8}} \quad \ldots\ldots (13)$$

For the tangent modulus at 25 per cent of the compressive strength the equation becomes,

$$E_{t25} = 66\,000\, S^{\frac{1}{2}} \quad \ldots\ldots (14)$$

The ratio of modulus of elasticity to strength as shown by these equations varies from about 3300 for the initial tangent for 500-lb. per sq. in. concrete, to 1400 for 5000-lb. concrete; the corresponding values for the tangent modulus at 25 per cent of the compressive strength are about 3000 to 940, respectively.

3. A study of the different variables affecting the strength and modulus of elasticity of concrete further emphasizes the relation shown in Eq. 8.

(*a*) Both the modulus of elasticity and strength increase within certain limits as the aggregate becomes coarser, although the modulus of elasticity increases less rapidly than the strength.

(*b*) An increase in the quantity of cement in the batch causes an increase in values of modulus of elasticity and strength. The modulus of elasticity is affected somewhat less by change in the cement content than the strength.

(*c*) The quantity of mixing water exerts a marked effect on the modulus of elasticity and strength. An addition of 25 per cent of water to a mixture

of normal consistency decreases the modulus of elasticity about 15 to 20 per cent, and the strength about 35 to 40 per cent.

(*d*) Both the modulus of elasticity and strength increase with the age of the concrete, so long as the specimens are kept moist during curing. The strength increases in proportion to the logarithms of the age. The modulus of elasticity follows approximately the same relation.[1]

(*e*) There is no marked difference in the modulus of elasticity and strength of concrete made from high-grade pebbles, crushed limestone, crushed granite or blast furnace slag.

(*f*) A comparison of specimens stored 14 days in damp sand and 77 days in air with specimens stored 91 days in damp sand shows both the modulus of elasticity and strength are higher for the damp sand storage.

(*g*) Tests for mixing times ranging from ¼ to 10 minutes show both the modulus of elasticity and strength to be greater for the longer mixing times.

4. The secant and tangent moduli of elasticity are less for the higher loads. At a given percentage of the strength these values vary approximately in direct proportion to initial tangent modulus for concrete of ordinary strengths.

5. Deformations measured over gage lengths ranging from 4 to 10 in. on a 6 by 12-in. cylinder show that the gage length exerts only a slight influence on the modulus of elasticity.

6. The inter-relation of modulus of elasticity to strength and the proportions of the concrete is sufficiently definite to make possible the construction of a nomographic chart. While the absolute values given on this diagram cannot be taken to be representative of concrete made under all conditions, it gives values which stand in the proper relation to each other.

7. A study of the stress-deformation data for a great number of materials, including woods, metals, stone, brick, brick piers, rubber, rope, and concrete of many kinds, indicates that the relation expressed by Eq. 1 is applicable to all materials.

8. A study of the action of the 2 extensometers used for these tests showed that the Ames dial gave much more uniform results than the Johnson wire-wound dial.

9. Values of modulus of elasticity should be the average of 10 or more tests in order to secure concordant results.

10. The point where the law expressed by Eq. 1 no longer holds is approximately the same as that called the "yield point" of concrete by certain writers. Values of "yield point" obtained in this way varied from 50 to 90 per cent of the compressive strength.

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[1] (Note to Revised Edition.) Tests reported in Table 4 and platted in Fig. 21 show the modulus of elasticity at 5 years to be lower than at 3 years. The reason for this discrepancy has not been satisfactorily explained. In general the strength increased for all ages up to 5 years.

TABLE 1.—TESTS OF CEMENT.

The portland cement consisted of a mixture of equal parts of 4 brands purchased in Chicago.
All tests made in accordance with standard methods of the American Society for Testing Materials.

MISCELLANEOUS TESTS.

Cement Lot No.	Used in Series.	Concrete Tests Reported in Table.	Fineness Residue on No. 200 Sieve.	Normal Consistency, per cent by weight.	Time of Setting.				Soundness Test (over boiling water).
					Vicat Needle		Gillmore Needle		
					Initial h m	Final h m	Initial h m	Final h m	
3909	83	4	19.3	23.0	3 15	6 30	5 00	7 25	O.K.
3965	89, 93	5, 6, 7, 8	18.8	23.0	3 40	7 36	5 15	8 32	"
4035	96, 97, 98, 99	9, 10, 11, 12,	17.5	23.0	3 45	9 00	6 00	9 30	"
4135	104	13	18.0	23.0	.....	.....	.....	.....	.....
4235	114	14	19.9	23.0	3 13	6 6	3 57	7 7	"
Average.....			18.7	23.0	3 30	7 18	5 3	8 8	

MORTAR STRENGTH TESTS.
1:3 standard sand mortar.

Cement Lot No.	Mixing Water, per cent.	Briquets, Tensile Strength, lb. per sq. in.							2 by 4-in. Cylinders, Compressive Strength, lb. per sq. in.						
		7 d.	28 d.	3 m.	6 m.	1 y.	2 y.	5 y.	7 d.	28 d.	3 m.	6 m.	1 y.	2 y.	5 y.
3909	10.3	310	387	408	450	397	367	380	1960	3390	4530	4790	4890	4160	4300
3965	10.3	242	378	462	440	387	369	360	1770	3360	4380	4570	4490	4650	3440
4035	10.3	246	386	402	424	374	341	355	1700	2640	3750	4120	3810	4320	4120
Average.	10.3	276	384	418	438	386	359	365	1810	3130	4210	4490	4400	4380	3950

TABLE 2.—MISCELLANEOUS DATA OF AGGREGATES.

The sieves were made of square mesh wire cloth manufactured by The W. S. Tyler Co. Each sieve has a clear opening of twice the width of the preceding sieve. In the order given at the head of the table and beginning with 100 the widths of clear openings in inches are as follows: 0.0058, 0.0116, 0.023, 0.046, 0.093, 0.185, 0.37, 0.75 and 1.5.

Size.	Kind.	Used in Series.	Concrete Tests in Table	Weight lb. per cu. ft.	Sieve Analysis. (Percent Coarser than Each Sieve.)									Fineness Modulus.[c]
					100[a]	48[b]	28[b]	14[b]	8	4	3/8	3/4	1½	
0—1½	Sand and Pebbles	83	4	131	99	97	87	81	74	67	55	40	0	6.00
0— 3/4	Sand and Pebbles	83	4	127	99	94	77	64	52	40	24	0	....	4.50
0—4	Sand	83	4	115	99	90	61	40	20	0	....	....	....	3.10
0—1½	Sand and Limestone	83	4	130	100	96	84	75	66	58	51	20	0	5.50
0—1½	Sand and Pebbles	89	5	130	100	97	89	84	79	56	50	18	0	5.73
0—14	Sand	93	6, 7, 8	104	98	89	42	0	....	....	....	....	....	2.29
0—8	Sand	93	6, 7, 8	110	99	92	58	28	0	....	....	....	....	2.77
0—4	Sand	93	6, 7, 8	115	99	94	70	48	28	0	....	....	....	3.39
0— 3/8	Sand and Pebbles	93	6, 7, 8	124	99	95	77	60	44	23	0	....	....	3.98
0— 3/4	Sand and Pebbles	93	6, 7, 8	126	100	96	79	75	65	51	31	0	....	4.97
0—2	Sand and Pebbles	93	6, 7, 8	128	100	99	94	90	86	80	60	40	20	6.69
0—1½	Sand and Pebbles	96, 97	9	130	100	98	90	82	76	66	49	16	0	5.77
0—1½	Sand and Pebbles	98	10, 11	126	99	98	91	85	80	73	51	22	0	6.00
0—1½	Sand and Limestone	98	10, 11	121	99	98	91	85	80	73	51	22	0	6.00
0—1½	Sand and Slag	98	10, 11	117	99	98	91	85	80	73	51	22	0	6.00
0—1½	Sand and Granite	98	10, 11	115	99	98	91	85	80	73	51	22	0	6.00
0—28	Sand	98	10, 11	102	87	33	0	....	....	....	....	....	....	1.20
0—14	Sand	98	10, 11	105	93	87	40	0	....	....	....	....	....	2.20
0—8	Sand	98	10, 11	108	95	90	55	25	0	....	....	....	....	2.65
0—4	Sand	98	10, 11	112	96	93	66	45	25	0	....	....	....	3.25
0— 3/8	Sand and Pebbles	98	10, 11	121	98	96	82	69	59	46	0	....	....	4.50
0— 3/4	Sand and Pebbles	98	10, 11	124	99	97	89	80	74	65	36	0	....[d]	5.40
0—1¼	Sand and Pebbles	98	10, 11	125	99	98	90	85	80	72	49	17	7[d]	5.90
0—1½	Sand and Pebbles	99	12	134	100	98	90	82	76	67	47	20	0	5.80
0—28	Sand	104	13	102	87	33	0	....	....	....	....	....	....	1.20
0—14	Sand	104	13	105	93	87	40	0	....	....	....	....	....	2.20
0—8	Sand	104	13	108	95	90	55	25	0	....	....	....	....	2.65
0—4	Sand	104	13	112	99	93	58	33	17	0	....	....	....	3.00
0— 3/8	Sand and Pebbles	104	13	121	99	95	72	55	44	35	0	....	....	4.00
0— 3/4	Sand and Pebbles	104	13	124	100	97	83	70	65	55	30	0	....	5.00
0—1½	Sand and Pebbles	104	13	126	100	98	87	79	74	69	48	20	0	5.75
0—1½	Sand and Pebbles	104	13	119	99	95	69	50	38	25	17	7	0	4.00
0—1½	Sand and Pebbles	104	13	125	99	96	79	66	59	50	36	15	0	5.00
0—1½	Sand and Pebbles	104	13	126	100	97	84	75	69	63	43	19	0	5.50
0—1½	Sand and Pebbles	104	13	126	100	98	87	79	74	69	48	20	0	5.75
0—1½	Sand and Pebbles	104	13	128	100	98	89	83	79	75	53	23	0	6.00
0—1½	Sand and Pebbles	104	13	125	100	99	92	87	84	82	57	24	0	6.25
0—1½	Sand and Pebbles	104	13	120	100	99	95	92	90	88	60	26	0	6.50
0—14	Sand	114	14	105	97	89	34	0	....	....	....	....	....	2.20
0—8	Sand	114	14	108	97	90	50	23	0	....	....	....	....	2.60
0—4	Sand	114	14	112	98	93	60	39	20	0	....	....	....	3.10
0— 3/8	Sand and Pebbles	114	14	121	99	96	79	68	59	49	0	....	....	4.50
0— 3/4	Sand and Pebbles	114	14	124	99	97	86	78	71	65	44	0	....	5.40
0—1½	Sand and Pebbles	114	14	128	99	98	87	80	74	68	51	18	0	5.75

a Number of openings per linear inch.

b (Note to Revised Edition.) The No. 48, 28 and 14-mesh sieves are identical with No. 50, 30, and 16 now used in the "Tentative Method of Test for Sieve Analysis of Aggregates for Concrete" of the American Society for Testing Materials. The No. 50, 30 and 16 sieves are now used in all our tests.

c Sum of percentages in sieve analysis divided by 100.

d Retained on 1-in. sieve; not used in calculating fineness modulus.

TABLE 3.—TYPICAL STRESS-DEFORMATION RELATION FOR CONCRETE.
(Data from Series 120.)

Compression tests of 6 by 12-inch cylinders.
For details of tests see Fig. 3.

Unit Stress, lb. per sq. in.	Unit Deformation, inches per inch.									
	190 C		187 C		188 C		221 C		224 C	
	Experimental.	Calculated.	Experimental.	Calculated.	Experimental.	Calculated.	Experimental.	Calculated.	Experimental.	Calculated.
0	0	0	0	0	0	0	0	0	0	0
100	0.00001	0.00001	0.00001	0.00001	0.00002	0.00001	0.00003	0.00003	0.00002	0.00002
200	2	3	2	2	2	3	6	7	8	8
300	5	5	4	4	5	5	11	11	12	12
400	6	7	5	6	6	7	16	16	17	17
500	10	10	8	8	9	9	21	21	22	24
600	12	12	10	10	12	12	26	26	31	31
700	13	14	12	12	13	14	31	31	40	38
800	18	17	13	14	14	16	38	38	47	46
900	21	20	16	16	18	18	42	43	60	54
1000	22	22	18	18	22	21	49	49	75	63
1500	38	36	31	30	34	34	88	83	.....	.....
2000	52	52	43	43	48	48	.....	.....	.....	.....
2500	68	68	55	55	62	63	.....	.....	.....	.....
3000	79	84	68	68	74	76	.....	.....	.....	.....
3500	95	102	87	83	88	91	.....	.....	.....	.....
4000	.....	.....	172	96	104	107	.....	.....	.....	.....
4500	.....	.....	.....	.....	121	123	.....	.....	.....	.....
5000	.....	.....	.....	.....	142	141	.....	.....	.....	.....
Ultimate Strength, lb. per sq. inch.....	4 200		4 010		5 210		1 890		1 060	
n.....	0.824		0.810		0.844		0.812		0.715	
K, lb. per sq. in..	1 030 000		1 040 000		1 260 000		478 000		196 000	

TABLE 4.—MODULUS OF ELASTICITY OF CONCRETE.

(Consistency, Size of Aggregate, Age; Series 83.)

Compression tests of 6 by 12-inch cylinders.
Hand-mixed concrete.
Mix 1-5 by volume.
Stored in damp sand; tested damp.
Aggregate: sand and pebbles from Elgin, Ill.; limestone from Chicago.
In general, each value is the average of 5 tests made on different days.
The 1-year modulus of elasticity values are the average of 2 or 3 tests.

Aggregate.		Mixing Water		Compressive Strength lb. per sq. in.							Initial Modulus of Elasticity 1000 lb. per sq. in.						
Size	Fineness Modulus.	Relative Consistency.	Water Ratio	7 d.	28 d.	6 m.	1 y.	2 y.	3 y.	5 y.	7 d.	28 d.	6 m.	1 y.	2 y.	3 y.	5 y.
SAND AND PEBBLES.																	
0—1½	6.00	0.80	0.66	2230	3250	3870	4430	4860	5510	4540	2750	4250	5820	....	5880	7770	6900
		0.90	0.74	2020	3560	4240	4580	5230	6540	6310	2730	4920	6160	6200	6800	6800	6480
		1.00	0.82	1660	3150	4370	4880	4960	5780	5870	3350	4300	4860	6000	6420	6070	6220
		1.10	0.91	1260	2720	3770	4370	4490	5480	5530	2640	4020	5520	4100	6720	6870	6200
		1.25	1.03	900	2220	3210	3330	3590	4370	4430	2970	3940	4600	4600	6360	6530	5660
		1.50	1.24	520	1340	2080	2290	2750	3780	2790	....	3300	4820	6800	6540	5370	4900
Average.				1430	2710	3590	3980	4310	5240	4910	2890	4120	5300	5540	6450	6570	6060
0—¾	4.50	0.70	0.74	1060	1890	2460	2780	3110	3240	3230	2670	3140	4040	4350	5340	4770	5160
		0.80	0.85	1070	2140	2820	3110	3590	3910	3610	2780	3590	3760	5950	6120	6780	5320
		0.90	0.95	990	2020	2930	3120	3510	4050	4100	2310	3150	4040	5550	5460	5970	5100
		1.00	1.06	790	1700	2730	2910	3450	3830	3850	2660	3550	4000	6200	5660	7400	5520
		1.10	1.17	630	1530	2490	2530	3050	3380	3510	2420	3850	3980	5000	5620	6200	5120
		1.25	1.33	470	1140	2030	2260	2790	2780	2910	1350	2820	3920	3800	5240	4730	4780
		1.50	1.60	330	880	1510	1870	2050	2240	2070	1410	2670	4120	3350	4640	4870	4080
Average.				760	1620	2420	2650	3080	3350	3330	2230	3250	3980	4890	5440	5820	5010
0—4	3.10	0.70	0.89	580	1060	1710	1830	2020	2190	2100	1420	2730	3760	4850	3140	3500	3380
		0.80	1.02	530	1090	1740	1810	2350	2240	2240	1610	3350	3440	3570	3840	3820	3680
		0.90	1.15	510	1120	1770	2030	2270	2320	2350	1200	2840	3820	4400	4160	3950	3420
		1.00	1.28	420	990	1500	1940	2080	2260	2390	1250	2400	3720	3550	3880	4070	3530
		1.10	1.40	350	810	1380	1520	1910	1850	2060	1470	2020	2740	3370	3980	3570	3420
		1.25	1.60	260	580	1240	1470	1610	1840	1630	810	1900	2380	3330	3160	3930	3000
		1.50	1.92	180	490	910	1120	1170	1400	1320	740	1550	2460	2670	2400	2750	2800
Average.				400	880	1460	1670	1920	2010	2010	1210	2400	3190	3680	3510	3660	3320
SAND AND CRUSHED LIMESTONE.																	
0—1½	5.50	0.70	0.63	1280	1970	2490	2740	2580	3180	3540	2820	3190	4080	4370	5700	4750	5060
		0.80	0.72	1350	2500	3350	3540	3760	3760	3730	2500	3810	4520	6030	6600	5980	5700
		0.90	0.81	1590	2650	3820	3630	5260	5580	5060	5340	4100	5380	5600	6030	6600	6300
		1.00	0.90	1360	2720	3480	4540	5110	5900	5740	3270	4300	5320	5830	6930	6350	6040
		1.10	0.99	1100	2410	3820	4330	4860	5420	5610	3600	4950	5080	5930	6470	6500	6180
		1.25	1.13	730	1610	3040	3290	3760	4220	4220	2470	4130	5760	4830	6380	6450	6240
		1.50	1.35	420	1010	1710	2040	2400	3080	2560	1220	3100	4600	4330	6280	5720	5400
Average.				1120	2120	3100	3440	3960	4450	4350	3030	3940	4960	5260	6340	6050	5850

TABLE 5.—MODULUS OF ELASTICITY OF CONCRETE.

(Consistency, Age; Series 89.)[1]

Compression tests of 6 by 12-in. concrete cylinders.
Machine-mixed concrete.
Mix 1:4 by volume.
Stored in damp sand, tested damp.
Aggregate: sand and pebbles from Elgin, Ill.; graded 0–1¼ in.
Each value is the average of 24 tests from 6 mixing times from ¼ to 10 min.

Mixing Water.		Compressive Strength, lb. per sq. in.			Initial Tangent Modulus of Elasticity, 1000 lb. per sq. in.		
Relative Consistency.	Water Ratio.	7 d.	28 d.	2 m.	7 d.	28 d.	2 m.
0.90	0.66	1870	3480	4070	3400	5440	5630
1.00	0.72	1390	2710	3470	3790	3990	5220
1.10	0.80	1200	2460	3170	3010	4480	4560
1.25	0.91	960	1850	2570	2680	3360	4590
1.50	1.08	510	1080	1660	1740	4260	3850
2.00	1.45	190	560	920	....	3020	3480
Average.....		1020	2020	2640	2920	4090	4560

[1] For details see "Effect of Time of Mixing on the Strength and Wear of Concrete," by D. A. Abrams, Proc. Am. Concrete Inst., 1918.

TABLE 6.—MODULUS OF ELASTICITY OF CONCRETE.

(Time of Machine Mixing.)

Compression tests of 6 by 12-inch concrete cylinders.
Stored in damp sand; tested damp.
Aggregate: Sand and pebbles from Elgin, Ill.; graded 0—1¼ inch.
For Series 89, each value is the average of 24 tests from 6 consistencies, for a 1:4 mix.
For Series 93, each value is the average of 60 tests from 8 mixes and 7 gradings.

Time of Mixing, min.	Compressive Strength, lb. per sq. in.					Initial Tangent Modulus of Elasticity, 1000 lb. per sq. in.				
	7 d.	28 d.	2 m.	3 m.	1 y.	7 d.	28 d.	2 m.	3 m.	1 y.
Data from Series 89.[1]										
10	1450	2570	3210	....	....	3090	4180	4700	....	....
5	1280	2470	3040	....	....	3090	4490	4550	....	....
2	1010	2020	2670	....	....	2970	4400	3960	....	....
1	1010	2140	2760	....	....	2750	4390	4840	....	....
½	840	1820	2500	....	....	3010	4080	4990	....	....
¼	790	1610	2230	....	....	2340	3320	4210	....	....
Average	1060	2100	2740	....	....	2880	4140	4540	....	....
Data from Series 93[1]										
10	1010	1860	....	2800	3760	2290	3380	....	5740	....
5	830	1750	....	2880	3740	2330	3610	....	4490	6350
2	650	1540	....	2630	3440	1840	2950	....	4240	5960
1	480	1440	....	2450	3340	1890	2750	....	3460	5480
½	430	1200	....	2200	2950	1470	2630	....	3460	4990
¼	380	1080	....	1950	2640	1530	2410	....	3550	4870
Average	630	1480	....	2480	3310	1890	2960	....	4160	5530

[1] For details see "Effect of Time of Mixing on the Strength and Wear of Concrete," by D. A. Abrams, Proc. Am. Concrete Inst., 1918.

TABLE 7.—MODULUS OF ELASTICITY OF CONCRETE.
(Quantity of Cement, Size of Aggregate, Age; Series 93.)[1]

Compression tests of 6 by 12-inch cylinders.
Machine-mixed concrete.
Mix by volume.
Relative consistency, 1.10.
Aggregate: sand and pebbles from Elgin, Ill.
Stored in damp sand; tested damp.
Each value is the average of 24 tests from 6 mixing times from ¼ to 10 min.

Mix by Vol.	Aggregate. Size.	Aggregate. F. M.	Water Ratio.	Compressive Strength, lb. per sq. in. 7 d.	28 d.	3 m.	1 y.	Initial Tangent Modulus of Elasticity, 1000 lb. per sq. in. 7 d.	28 d.	3 m.	1 y.
QUANTITY OF CEMENT.											
1:2....	0–1½	5.75	0.60	1760	3600	5380	6540	3620	4170	4720	7440
1:3....	.....	....	0.70	1310	2990	4720	5740	3700	4050	5320	8070
1:4....	.....	....	0.81	960	2270	3780	4950	2930	3880	5160	7160
1:5....	.....	....	0.91	760	1830	3030	4170	2250	3680	4740	6750
1:6....	.....	....	1.01	700	1740	2820	3740	2030	3420	5300	6870
1:7....	.....	....	1.10	640	1520	2490	3580	2940	3940	4730	6560
1:9....	.....	....	1.32	390	950	1710	2420	1380	3290	4160	5930
1:15...	.....	....	1.94	180	410	710	1090	720	1800	3060	3220
Average.....				840	1910	3080	4030	2450	3530	4650	6500
SIZE OF AGGREGATE.											
1:5...	0–14	2.30	1.57	120	310	640	980	460	1060	2000	2000
	0–8	2.80	1.51	160	410	830	1310	600	1220	2100	2430
	0–4	3.40	1.43	200	500	1100	1570	780	1700	2370	3060
	0–⅜	4.00	1.25	320	890	1830	2660	970	2430	3580	4660
	0–¾	5.00	1.08	470	1300	2600	3290	1610	2940	4240	6350
	0–1½	5.75	0.91	760	1830	3030	4170	2250	3680	4740	6750
	0–2	6.70	0.82	850	1990	3150	4300	2500	3800	5280	6940
Average.....				410	1030	1880	2610	1310	2400	3470	4600

[1] For details see "Effect of Time of Mixing on the Strength and Wear of Concrete," by D. A. Abrams, Proc. Am. Concrete Inst. 1918.

TABLE 8.—MODULUS OF ELASTICITY OF CONCRETE.

(Quantity of Cement, Size of Aggregate, Age; Series 93.)[1]

Compression tests of 6 by 12-inch cylinders.
Hand-mixed concrete.
Mix by volume.
Relative consistency, 1.10.
Aggregate: Sand and pebbles from Elgin, Ill.
Stored in damp sand; tested damp.
Each value is the average of 4 tests made on different days.

Mix by Vol.	Aggregate.		Water Ratio.	Compressive Strength, lb. per sq. in.				Initial Tangent Modulus of Elasticity, 1000 lb. per sq. in.			
	Size.	F. M.		7 d.	28 d.	3 m.	1 y.	7 d.	28 d.	3 m.	1 y.
Quantity of Cement.											
1:2....	0–1½	5.75	0.50	1560	3380	5060	6400	3500	3320	5820	4900
1:3....	....	....	0.70	1300	2780	4200	6000	3050	3320	5400	6080
1:4....	....	....	0.81	940	2180	3660	4600	2420	4000	5120	7220
1:5....	....	....	0.91	760	1950	3480	4400	2350	2950	4950	7100
1:6....	....	....	1.01	580	1670	3090	3800	1900	3750	5350	6880
1:7....	....	....	1.10	530	1430	2550	3220	2020	2800	5600	6570
1:9....	....	....	1.32	360	1030	1870	2450	2130	4100	4200	5350
1:15....	....	....	1.94	190	440	800	1030	800	2270	2930	2870
Average.....				780	1860	3090	3990	2270	3310	4920	5870
Size of Aggregate.											
1:5...	0–14	2.30	1.57	140	380	870	1350	380	1700	2530	2580
	0–8	2.80	1.51	160	500	950	1480	600	2230	2000	2680
	0–4	3.40	1.43	180	600	1310	1890	800	2070	2950	3430
	0–⅜	4.00	1.25	270	900	1720	2540	1170	1700	3600	5700
	0–¾	5.00	1.08	440	1260	2550	2960	2850	2520	4000	7850
	0–1½	5.75	0.91	760	1950	3480	4400	2350	2950	4950	7100
	0–2	6.70	0.82	670	2000	3500	4760	1800	3320	4800	6700
Average.....				370	1080	2060	2770	1420	2360	3550	5150

[1] For details see "Effect of Time of Mixing on the Strength and Wear of Concrete," by D. A. Abrams, Proc. Am. Concrete Inst., 1918.

TABLE 9.—MODULUS OF ELASTICITY OF CONCRETE.
(Consistency—Age.)

Compression tests of 6 by 12-inch cylinders.
Machine-mixed concrete.
Mix by volume.
Stored in damp sand; tested damp.
Aggregate: sand and pebbles from Elgin, Ill.; graded 0–1½ in.
For Series 96, each value is the average of 24 tests from 6 rates of rotation of mixer drum from 8 to 30 r.p.m.
For Series 97, each value is the average of 105 tests from 21 temperatures of mixing water from 0 to 100° C.

Mixing Water.		Compressive Strength, lb. per sq. in.				Initial Tangent Modulus of Elasticity, 1000 lb. per sq. in.		
Relative Consistency.	Water Ratio.	7 d.	28 d.	3 m.	1 y.	28 d.	3 m.	1 y.
Mix 1:5—Data from Series 96[1].								
1.00	0.83	1120	2670	4160	5180	3290	5210	6070
1.10	0.91	720	2080	3220	4280	3790	4550	5730
1.10	0.91	740	1930	3300	4140	4190	5350	5280
1.10	0.91	830	2010	3080	4100	3850	5520	5720
1.25	1.04	560	1410	2770	3570	3380	4870	5230
1.50	1.21	360	970	1780	2660	3430	4240	4840
Average.....		720	1840	3050	3990	3660	4960	5480
Mix 1:4—Data from Series 97.[1]								
0.90	0.68	1740	3440	4740	....	4300	5700	....
1.00	0.76	1370	3080	4380	....	3910	5350	....
1.10	0.83	1120	2720	4090	....	3740	5320	....
1.25	0.95	950	2160	3450	....	3470	4830	....
Average.....		1300	2850	4160	....	3860	5300	....

[1] For details see "Effect of Time of Mixing on the Strength and Wear of Concrete, by D. A. Abrams, Proc. Am. Concrete Inst., 1918.

TABLE 10.—MODULUS OF ELASTICITY OF CONCRETE.

(Mix and Kind of Aggregate—Series 98.)

Compression tests of 6 by 12-inch cylinders.
Mix by volume.
Fine aggregate; 0-No. 4 sand from Elgin, Ill.
Coarse aggregate; No. 4–1½ in.
Relative consistency, 1.10.
Age at test 3 months.
Each value for air-stored specimens is the average of 2 tests made on different days.
Each value for sand-stored specimens is the average of 3 tests made on different days.

Mix by Vol,	Water Ratio.	Stored in Sand 14 d., Air 77 d.					Stored in Sand 3 m.					Average of all Conditions.
		Limestone.	Pebbles.	Slag.	Granite.	Average.	Limestone.	Pebbles.	Slag.	Granite.	Average.	
COMPRESSIVE STRENGTH, LB. PER SQ. IN.												
1:6	1.04	2120	2160	1790	2020	2020	2560	2690	2820	2440	2620	2320
1:5	0.92	2880	2890	2460	2340	2640	3550	3360	2970	3350	3310	2970
1:4½	0.87	3320	3040	2820	2870	3010	3660	3660	3590	3680	3640	3340
1:4	0.82	3250	3740	3620	3590	3550	4180	4110	3810	4390	4120	3840
1:3½	0.77	4510	3980	4100	4740	4330	4520	4400	4470	4080	4370	4350
1:3	0.71	4750	5060	4620	5230	4920	4870	4390	4660	5340	4820	4870
1:2	0.61	5140	4520	5440	4980	5020	5700	5320	6060	6160	5810	5420
Average.....		3710	3630	3550	3680	3640	4150	3990	4050	4260	4100	3870
"INITIAL TANGENT" MODULUS OF ELASTICITY, 1000 LB. PER SQ. IN.												
1:6	1.04	3500	4800	3500	5300	4280	5800	5000	4900	5230	5230	4750
1:5	0.92	5000	5700	4600	5500	5200	5900	5500	5430	7200	6010	5600
1:4½	0.87	4600	6200	5500	5400	5420	5900	5000	5500	6500	5720	5570
1:4	0.82	5800	4800	4100	5700	5100	7600	5900	6000	5700	6300	5700
1:3½	0.77	7500	4800	6700	4800	5950	6600	6200	6000	5600	6100	6020
1:3	0.71	6500	4800	5200	4800	5320	6200	5900	6900	6600	6400	5860
1:2	0.61	5700	4800	6700	7000	6050	6600	6200	7100	5500	6350	6200
Average.....		5510	5130	5190	5500	5330	6370	5670	5980	6050	6020	5670
TANGENT MODULUS OF ELASTICITY AT 25 PER CENT LOAD, 1000 LB. PER SQ. IN.												
1:6	1.04	2820	3780	3200	3270	3270	4520	4380	3780	3510	4050	3660
1:5	0.92	2870	3540	2890	3400	3180	4610	4720	4730	4940	4750	3970
1:4½	0.87	2920	4950	3370	3680	3730	4450	3980	4110	4740	4320	4030
1:4	0.82	3740	2880	2680	4860	3540	5890	4200	4720	3730	4640	4090
1:3½	0.77	5600	2770	5200	2900	4120	3500	4570	5540	4890	4620	4370
1:3	0.71	4500	3140	3730	4280	3910	4510	4040	5360	5300	4800	4360
1:2	0.61	3760	2910	3960	4500	3780	5250	4160	5780	3400	4650	4220
Average.....		3740	3420	3580	3840	3650	4680	4290	4860	4360	4550	4100

TABLE 11.—MODULUS OF ELASTICITY OF CONCRETE.

(Grading and Size of Aggregate; Series 98.)

Compression tests of 6 by 12-inch cylinders.
Hand-mixed concrete.
Mix 1:4 by volume.
Relative consistency, 1.10.
Aggregate: sand and pebbles from Elgin, Ill.
Average of specimens stored 14 days and 90 days in damp sand.
Age at test 3 months.
In general, each value is the average of 5 tests made on different days.

Size of Aggregate.	Fineness Modulus of Aggregate.	Water Ratio.	Compressive Strength, lb. per sq. in.	Initial Tangent Modulus, 1000 lb. per sq. in.	Tangent Modulus at 25 per cent load 1000 lb. per sq. in.
0–1½	4.00	1.04	2130	4570	3340
	5.00	0.92	3170	4840	3590
	5.50	0.88	3560	5440	3980
	5.75	0.85	3650	5530	4020
	6.00	0.82	3610	5360	3910
	6.25	0.80	3550	5320	3940
0–28	1.20	1.33	890	1900	1800
0–14	2.20	1.22	1380	2300	1920
0–8	2.65	1.18	1790	4300	2940
0–4	3.25	1.10	2230	4700	3580
0–⅜	4.50	0.98	3430	5400	4400
0–¾	5.40	0.89	3410	4600	3400
0–1¼	5.90	0.83	3650	5300	4470
0–1½	6.00	0.82	3560	5800	3900

TABLE 12.—MODULUS OF ELASTICITY OF CONCRETE.

(Mix and Gage Length—Series 99.)

Compression tests of 6 by 12-inch cylinders.
Hand-mixed concrete.
Mix by volume.
Aggregate: sand and pebbles from Elgin, Ill.; graded 0–1½ in.
Relative consistency, 1.00.
Specimens stored in damp sand; tested damp.
Age at test, 28 days.
Each value is the average of 20 tests made on different days.
K and *n* are factors in Eq. 1, page 9.

Extensometer Gage Length, in.	Water Ratio.	Compressive Strength lb. per sq. in.	Value of *K* in 1000 lb. per sq. in.	Value of *n*.	Modulus of Elasticity, 1000 lb. per sq. in.										
					Initial Tangent.	For Different Percentages of Load.									
						Tangent Modulus.					Secant Modulus.				
						5	10	15	25	50	5	10	15	25	50
Mix 1:7.															
4	1.06	1740	419	0.756	3800	4900	3920	3400	2840	2290	6460	5250	4510	3760	2980
6		1810	475	0.773	3810	5070	3880	3540	2880	2280	7040	5350	4580	3810	2940
8		1830	500	0.784	3650	4640	3720	3280	2820	2360	6200	4960	4360	3700	3080
10		1750	594	0.804	3610	4430	3640	3290	2720	2290	5920	4640	4050	3450	2860
Average.....		1780	....	.....	3720	4760	3790	3380	2820	2310	6400	5050	4380	3680	2970
Mix 1:5.															
4	0.86	2700	942	0.839	4240	4480	3910	3540	3210	2840	5520	4640	4270	3870	3410
6		2550	689	0.802	4280	4870	3720	3500	3140	2850	7390	5050	4500	3930	3340
8		2530	525	0.770	4080	5180	4050	3520	2990	2450	7310	5550	4740	3920	3140
10		2550	651	0.797	4120	4590	3780	3360	2920	2480	6030	4880	4310	3710	3100
Average.....		2580	....	.....	4180	4780	3870	3480	3070	2660	6560	5030	4460	3860	3250
Mix 1:4.															
4	0.76	3100	1160	0.862	4490	4340	3780	3490	3280	2840	5150	4470	4130	3770	3350
6		3140	865	0.818	4510	5020	4140	3730	3310	2820	6460	5250	4690	4100	3450
8		3100	652	0.790	4090	5070	4090	3600	3070	2650	6900	5460	4680	3960	3280
10		3150	976	0.841	4300	4320	3710	3410	3090	2780	5320	4510	4120	3690	3220
Average.....		3120	....	.....	4350	4690	3930	3560	3190	2770	5960	4920	4400	3880	3320
Mix 1:3.															
4	0.66	3520	905	0.821	4790	4830	4100	3720	3320	2850	6000	5040	4560	4050	3470
6		3370	965	0.830	4600	4630	3960	3540	3280	2840	5680	4830	4410	3950	3420
8		3480	1420	0.871	4490	4320	3790	3590	3260	2930	5390	4680	4340	3930	3480
10		3560	1370	0.873	4620	4560	3920	3640	3270	2900	5360	4590	4220	3790	3330
Average.....		3480	....	.....	4620	4590	3940	3620	3280	2880	5610	4780	4380	3930	3420

TABLE 13.—MODULUS OF ELASTICITY OF CONCRETE.

(Size and Grading of Aggregate, Mix and Consistency; Series 104.)

Compression tests of 6 by 12-inch concrete cylinders.
Hand-mixed concrete.
Mix by volume.
Stored in damp sand; tested damp.
Aggregate: sand and pebbles from Elgin, Ill.
Each value is the average of 5 tests made on different days.
Age at test 28 days.
K and n are factors in Eq. 1, page 9.

Aggregate.		Mixing Water.		Compressive Str'gth lb. per sq. in.	Value of K in 1000 lb. per sq. in.	Value of n.	Modulus of Elasticity, 1000 lb. per sq. in.										
							Initial Tangent.	For Different Percentages of Load.									
								Tangent Modulus.					Secant Modulus.				
Size.	F. M.	Relative Consistency.	Water Ratio.					5	10	15	25	50	5	10	15	25	50
Mix 1:5.																	
0–28	1.20	1.00	1.42	370	675	0.951	1130	1130	1070	1060	1030	1000	1190	1120	1120	1080	1050
0–14	2.25	1.00	1.29	550	464	0.884	1420	1350	1310	1250	1200	1120	1510	1460	1390	1320	1230
0–8	2.65	1.00	1.24	740	620	0.894	1820	1870	1660	1560	1460	1370	2160	1910	1790	1670	1560
0–4	3.00	1.00	1.20	960	585	0.857	2320	2500	2130	1980	1780	1620	3000	2540	2360	2090	1920
0–⅜	4.00	1.00	1.08	1370	843	0.874	2920	2990	2670	2490	2340	2110	3440	3070	2860	2680	2410
0–¾	5.00	1.00	0.96	2230	1230	0.875	4480	4140	3670	3420	3170	2940	4810	4250	3950	3650	3380
0–1½	5.75	1.00	0.88	2600	1590	0.897	4400	4230	3900	3750	3560	3320	4720	4310	4160	3940	3670
Average				1260	....	....	2640	2600	2340	2220	2080	1930	2980	2670	2520	2350	2170
Mix 1:3.																	
0–28	1.20	1.00	0.99	1020	810	0.889	2500	2510	2230	2170	1980	1810	2870	2540	2470	2260	2060
0–14	2.25	1.00	0.92	1620	1118	0.895	3080	3070	2870	2740	2590	2430	3400	3180	3030	2860	2690
0–8	2.65	1.00	0.89	1810	1058	0.887	3270	3060	2600	2610	2510	2250	3480	2950	2960	2840	2550
0–4	3.00	1.00	0.87	2330	941	0.857	4000	3650	3220	3040	2810	2480	4280	3760	3550	3270	2880
0–⅜	4.00	1.00	0.80	3460	1608	0.902	4680	3930	3640	3520	3310	3120	4350	4030	3890	3660	3460
0–¾	5.00	1.00	0.72	4020	1557	0.901	4440	3780	3510	3410	3230	2930	4200	3900	3790	3590	3250
0–1½	5.75	1.00	0.67	4140	1502	0.893	4480	3900	3560	3440	3210	2900	4390	4000	3860	3590	3240
Average				2630	....	.....	3780	3410	3090	2990	2810	2560	3850	3480	3360	3150	2880
Mix 1:5.																	
0–1½	4.00	1.00	1.08	1510	1143	0.890	3480	3380	3150	2960	2770	2570	3860	3580	3360	3130	2890
0–1½	5.00	1.00	0.96	2250	1242	0.867	4580	4610	4070	3890	3550	3240	5340	4720	4500	4110	3750
0–1½	5.50	1.00	0.90	2650	1742	0.921	3900	3710	3460	3320	3230	3040	4050	3770	3610	3510	3290
0–1½	5.75	1.00	0.88	2830	1428	0.882	4580	4550	4000	3810	3460	3160	5200	4570	4350	3920	3600
0–1½	6.00	1.00	0.84	2730	1390	0.875	5080	4690	4140	3940	3640	3290	5420	4760	4520	4160	3750
0–1½	6.25	1.00	0.82	2300	1200	0.879	3940	3890	3480	3240	3090	2820	4520	3990	3700	3510	3180
0–1½	6.50	1.00	0.78	1680	1445	0.901	3300	3720	3550	3400	3220	2930	4140	3950	3780	3580	3250
Average				2280	....	.....	4120	4080	3690	3510	3280	3010	4650	4190	3970	3700	3390
Mix 1:7.																	
0–1½	5.75	0.90	0.97	2070	1153	0.862	4800	4790	4070	3720	3420	3040	5650	4790	4370	4000	3530
		1.00	1.08	1690	674	0.802	5180	5220	4420	3810	3360	2860	6850	5720	4870	4250	3580
		1.10	1.19	1400	902	0.846	4180	4830	4100	3660	3260	2840	6120	5160	4570	4030	3480
		1.25	1.35	940	603	0.831	3460	3840	3300	2990	2610	2210	4930	4210	3780	3270	2730
		1.50	1.62	770	453	0.814	3130	3820	2860	2550	2240	1910	5370	3790	3290	2810	2320
Average				1370	....	.....	4150	4500	3750	3350	2980	2570	5780	4730	4180	3670	3130
Mix 1:5.																	
0–1½	5.75	0.90	0.79	3260	1089	0.853	5060	4370	3660	3550	3280	2960	5220	4330	4170	3820	3430
		1.00	0.88	2770	1442	0.888	4440	4270	3900	3670	3490	3160	4820	4390	4130	3930	3560
		1.10	0.96	2090	1104	0.849	4820	4830	4460	4020	3640	3230	5820	5350	4820	4310	3830
		1.25	1.09	1450	578	0.794	4520	4780	4050	3610	3170	2630	6100	5150	4570	4000	3300
		1.50	1.31	990	731	0.870	3450	2980	2560	2350	2150	1910	3650	3080	2820	2550	2230
Average				2110	....	.....	4460	4250	3730	3440	3150	2780	5120	4460	4100	3720	3270

(Continued on page 65)

TABLE 13—*Continued.*

Aggregate.		Mixing Water.		Compressive Str'gth lb. per sq. in.	Value of K in 1000 lb. per sq. in.	Value of n.	Modulus of Elasticity, 1000 lb. per sq. in.										
							Initial Tangent.	For Different Percentages of Load.									
								Tangent Modulus.					Secant Modulus.				
Size.	F. M.	Relative Consistency.	Water Ratio.					5	10	15	25	50	5	10	15	25	50
MIX 1:4.																	
0–1½	5.75	0.90	0.70	4180	1652	0.922	3360	3240	3060	3000	2860	2780	3510	3310	3240	3090	3000
		1.00	0.77	3340	1396	0.866	5360	4960	4470	4200	3810	3460	5750	5170	4860	4410	4000
		1.10	0.85	2760	1932	0.912	4600	4430	4100	4000	3770	3530	4870	4490	4380	4120	3850
		1.25	0.96	1640	984	0.852	4280	4270	3860	3520	3260	2930	5050	4550	4150	3840	3450
		1.50	1.16	1130	1072	0.894	3700	3180	2890	2750	2570	2350	3630	3270	3090	2870	2610
Average				2610	....	.....	4260	4020	3680	3490	3250	3010	4560	4160	3940	3670	3380
MIX 1:3.																	
0–1½	5.75	0.90	0.60	4690	2820	0.924	5220	4600	4340	4130	3930	3660	5030	4740	4510	4280	3980
		1.00	0.67	3950	1976	0.907	5320	4400	4250	4110	3910	3580	4860	4690	4530	4300	3920
		1.10	0.74	3570	2104	0.926	5060	4730	4430	4370	4190	3900	5090	4750	4680	4510	4200
		1.25	0.84	2520	1652	0.898	4600	4400	4040	3850	3690	3460	4910	4490	4280	4090	3840
		1.50	1.00	1570	800	0.847	4050	3600	3200	3000	2720	2320	4320	3810	3560	3200	2720
Average				3260	....	.....	4850	4350	4050	3890	3690	3380	4840	4500	4310	4080	3730
MIX 1:2.																	
0–1½	5.75	0.90	0.51	4780	1355	0.869	4800	4360	3900	3600	3380	3000	5130	4560	4210	3950	3480
		1.00	0.57	4500	1887	0.907	4780	4400	4060	3840	3720	3380	4920	4520	4270	4120	3740
		1.10	0.62	4070	1718	0.884	5320	4960	4440	4070	3940	3520	5730	5110	4660	4500	4010
		1.25	0.71	2790	1112	0.851	4760	4860	4210	3890	3600	3170	5780	4980	4590	4240	3720
		1.50	0.85	1840	1690	0.919	4020	3860	3610	3460	3280	3100	4320	4000	3810	3580	3370
Average				3600	....	.....	4740	4490	4040	3770	3580	3230	5180	4630	4310	4080	3660
MIX 1:1.																	
0–1½	5.75	0.90	0.42	5850	1342	0.888	4940	4220	3860	3670	3460	3050	4760	4350	4110	3890	3430
		1.00	0.46	5150	1725	0.903	4680	4110	3840	3660	3470	3250	4570	4270	4080	3860	3620
		1.10	0.51	5070	1164	0.876	3960	3420	3110	2990	2760	2360	3910	3560	3420	3150	2700
		1.25	0.58	3830	1982	0.916	4660	4290	4080	3950	3800	3600	4660	4430	4280	4120	3890
		1.50	0.70	3440	1990	0.934	3930	3630	3460	3440	3330	3180	3890	3700	3670	3550	3370
Average				4670	....	.....	4430	3930	3670	3540	3360	3090	4360	4060	3910	3710	3400
MIX 1:1/3																	
0–1½	5.75	0.90	0.35	6380	1267	0.873	4620	3770	3420	3230	2990	2680	4340	3940	3710	3420	3060
		1.00	0.39	6680	1274	0.876	4580	3560	3260	3100	2810	2520	4110	3740	3540	3210	2860
		1.10	0.43	5720	1726	0.905	4500	3870	3680	3630	3330	3100	4290	4080	3910	3670	3420
		1.25	0.49	5380	1377	0.908	3300	2960	2780	2660	2550	2350	3280	3070	2940	2810	2580
		1.50	0.59	4120	1094	0.859	4380	3830	3380	3170	2980	2620	4620	4040	3760	3510	3060
Average				5660	....	.....	4280	3600	3300	3160	2930	2650	4130	3770	3570	3320	3000
NEAT CEMENT.																	
		0.90	0.32	4140	1222	0.905	3400	2800	2640	2620	2510	2370	3070	2890	2870	2740	2080
		1.00	0.36	7600	1371	0.898	4200	3110	2820	2700	2500	2270	3470	3140	3000	2790	2530
		1.10	0.40	6630	867	0.854	3660	2860	2550	2350	2150	1900	3360	2990	2750	2510	2210
		1.25	0.45	6360	1106	0.876	4340	3020	2740	2600	2390	2180	3510	3140	2960	2700	2440
		1.50	0.54	4930	832	0.873	3120	2420	2220	2100	1950	1780	2760	2510	2360	2170	1960
Average				5930	....	.....	3740	2840	2590	2470	2300	2100	3230	2930	2790	2580	2340

TABLE 14.—MODULUS OF ELASTICITY OF CONCRETE.

(Consistency, Amount of Cement, Size of Aggregate; Series 114.)

Compression tests of 6 by 12-inch concrete cylinders.
Hand-mixed concrete.
Mix by volume.
Stored in damp sand; tested damp.
Aggregate; sand and pebbles from Elgin, Ill.
Each value is the average of 5 tests made on different days.
K and n are factors in Eq. 1, page 9.

Mix by Vol.	Aggregate.		Mixing Water.		Compressive Strength lb. per sq. in.					Initial Tangent Modulus 1000 lb. per sq. in.					Tangent Modulus at 25 per cent Load 1000 lb. per sq. in.				
	Size.	F. M.	Relative Consistency.	Water Ratio.	7 d.	28 d.	3 m.	1 y.	2 y.	7 d.	28 d.	3 m.	1 y.	2 y.	7 d.	28 d.	3 m.	1 y.	2 y.
1–4	0–1½	5.80	0.90	0.66	2440	3920	4400	6110	6420	4100	5400	6460	7660	8920	3520	3950	4740	5570	5400
			0.95	0.69	2150	3470	4410	5680	6590	3500	4800	5700	6920	7400	3190	3700	4710	5220	5460
			1.00	0.73	2090	3310	4580	4950	6470	4000	5400	5960	7640	6520	3310	4310	4690	5780	5380
			1.05	0.76	1850	3140	4430	4940	6190	3500	4400	6700	7940	6700	3090	3330	4590	5950	5500
			1.10	0.80	1570	3120	4130	4370	5440	3000	5300	5720	7580	6780	2590	4040	5470	5260	5630
			1.25	0.91	1080	2260	2950	3550	4160	2800	4080	5160	6980	6800	2490	3300	4280	5310	4730
			1.50	1.10	670	1320	2150	2800	3000	2300	2900	4600	5510	6180	2050	2620	3570	4230	4790
			2.00	1.46	400	860	1240	1560	1770	1100	2600	4060	6100	6130	.....	2650	3480	4610	4890
1–9	0–1½	5.80	1.00	1.23	570	1070	1480	1830	2080	1600	2700	3920	6780	5000	2820	3270	3290	4520	4600
1–6				0.93	....	2060	....	....	....	....	4500	....	....	....	....	3480	....	....	....
1–5				0.83	1470	2680	3460	4360	5040	3300	4900	5120	6540	7130	2830	3790	4230	5290	4840
1–4				0.73	2090	3310	4580	4950	6470	4000	5400	5960	7640	6520	3310	4310	4690	5780	5380
1–3				0.63	2620	4030	4690	5950	6990	4500	5600	6900	7640	7500	3390	4190	5160	6060	5530
1–2				0.53	....	4870	....	....	....	....	5500	....	....	....	....	4330	....	....	....
1–4	0–14	2.20	1.00	1.13	....	970	....	....	....	....	1800	....	....	....	....	1580	....	....	....
	0–8	2.60		1.07	....	1170	....	....	....	....	1900	....	....	....	....	1880	....	....	....
	0–4	3.10		1.00	....	1360	....	....	....	....	2700	....	....	....	....	2400	....	....	....
	0–⅜	4.50		0.83	....	2490	....	....	....	....	4200	....	....	....	....	3440	....	....	....
	0–¾	5.40		0.77	....	3530	....	....	....	....	4900	....	....	....	....	3760	....	....	....
	0–1½	5.80		0.73	2090	3310	4580	4950	6470	4000	5400	5960	7640	6520	3310	4310	4690	5780	5380

(Continued on page 67.)

TABLE 14.—MODULUS OF ELASTICITY OF CONCRETE—*Continued.*

Mix by Vol.	Aggregate.		Water.		Secant Modulus at 25 per cent Load 1000 lb. per sq. in.					Value of K in 1000 lb. per sq. in.					Value of n.				
	Size.	F. M.	Relative Consistency.	Water Ratio.	7 d.	28 d.	3 m.	1 y.	2 y.	7 d.	28 d.	3 m.	1 y.	2 y.	7 d.	28 d.	3 m.	1 y.	2 y.
			0.90	0.66	3720	4370	5100	6370	6860	2345	2000	2870	2620	3570	.947	.904	.930	.875	.823
			0.95	0.69	3300	4120	5210	6110	6120	2322	1738	2318	2250	3470	.966	.898	.905	.853	.897
			1.00	0.73	3550	4660	5180	7190	5820	1914	2415	2328	1700	3550	.932	.924	.906	.828	.925
			1.05	0.76	3300	3800	5230	6950	6020	1850	1227	1782	2480	3600	.937	.875	.877	.855	.910
1–4	0–1½	5.80	1.10	0.80	2660	4420	5960	5910	6100	2110	2080	2970	2640	3500	.971	.914	.918	.893	.924
			1.25	0.91	2650	3540	4700	5960	5630	1556	1910	2162	2700	2280	.940	.931	.910	.890	.851
			1.50	1.10	2300	2780	3920	5290	5670	830	1698	1762	1310	2200	.892	.944	.911	.804	.848
			2.00	1.46	....	3160	3760	5820	6090	596	668	1928	1240	1370	.956	.837	.926	.797	.806
1–9				1.23	3000	3710	3500	5470	4600	713	1038	2028	1480	4080	.921	.882	.940	.827	1.00
1–6				0.93	....	3820	....	....	....	....	1734	....	....	....	....	.912	....	....	....
1–5				0.83	2960	4220	4610	6030	5520	2042	1730	2223	2730	3060	.955	.899	.918	.870	.864
1–4	0–1½	5.80	1.00	0.73	3550	4660	5180	7190	5820	1914	2415	2328	1700	3550	.932	.924	.906	.828	.925
1–3				0.63	3640	4650	5700	6550	6290	1995	2046	2518	3670	3430	.931	.904	.905	.920	.910
1–2				0.53	....	4660	....	....	....	....	2558	....	....	....	....	.928	....	....	....
	0–14	2.20		1.13	....	1640	....	....	....	....	1462	....	....	....	....	.965	....	....	....
	0–8	2.60		1.07	....	1960	....	....	....	....	1397	....	....	....	....	.960	....	....	....
	0–4	3.10		1.00	....	2640	....	....	....	....	1186	....	....	....	....	.910	....	....	....
1–4	0–⅜	4.50	1.00	0.83	....	2710	....	....	....	....	1950	....	....	....	....	.928	....	....	....
	0–¾	5.40		0.77	....	4150	....	....	....	....	1875	....	....	....	....	.908	....	....	....
	0–1½	5.80		0.73	3550	4660	5180	7190	5820	1914	2415	2328	1700	3550	.932	.924	.906	.828	.925

TABLE 15.—RATIO OF MODULUS OF ELASTICITY OF CONCRETE TO COMPRESSIVE STRENGTH
(Data from Table 14)

Compression tests of 6 by 12-inch concrete cylinders.
Hand-mixed concrete.
Mix by volume.
Stored in damp sand; tested damp.
Aggregate; sand and pebbles from Elgin, Ill.
Each value is the average of 5 tests made on different days.

Mix by Vol.	Aggregate.		Water.		Ratio of Modulus of Elasticity to Ultimate Compressive Strength.														
					Initial Tangent.					Tangent at 25 per cent Load.					Secant at 25 per cent Load.				
	Size.	F. M.	Relative Consistency.	Water Ratio.	7 d.	28 d.	3 m.	1 y.	2 y.	7 d.	28 d.	3 m.	1 y.	2 y.	7 d.	28 d.	3 m.	1 y.	2 y.
1-4	0–1½	5.80	0.90	0.66	1680	1380	1470	1250	1390	1440	1010	1080	910	840	1520	1110	1160	1040	1070
			0.95	0.69	1630	1380	1290	1220	1120	1480	1070	1070	915	840	1530	1190	1180	1080	930
			1.00	0.73	1910	1630	1300	1540	1010	1580	1300	1020	1170	830	1700	1410	1130	1450	900
			1.05	0.76	1890	1400	1510	1610	1080	1670	1060	1030	1200	890	1780	1210	1180	1410	970
			1.10	0.80	1910	1690	1390	1740	1250	1650	1280	1330	1200	1040	1700	1410	1450	1350	1120
			1.25	0.91	2590	1810	1750	1970	1630	2300	1460	1450	1500	1130	2450	1570	1590	1680	1350
			1.50	1.10	3440	2200	2140	1970	2060	3060	1980	1660	1510	1600	3440	2100	1820	1890	1890
			2.00	1.46	2750	3020	3280	3910	3470	.....	3080	2800	2960	2760	.....	3680	3040	3740	3440
1-9	0–1½	5.80	1.00	1.23	2810	2520	2650	3700	2410	4950	3060	2220	2480	2210	5260	3470	2360	2990	2210
1-6				0.93	....	2190	....	....	....	....	1690	....	....	....	....	1850	....	....	....
1-5				0.83	2240	1830	1480	1500	1420	1920	1420	1220	1210	900	2010	1580	1330	1380	1090
1-4				0.73	1910	1630	1300	1540	1010	1580	1300	1020	1170	830	1700	1410	1130	1450	900
1-3				0.63	1720	1390	1470	1280	1070	1290	1040	1100	1020	790	1380	1150	1220	1100	900
1-2				0.53	....	1130	....	....	....	....	890	....	....	....	....	960	....	....	....
1-4	0–14	2.20	1.00	1.13	....	1860	....	....	....	....	1630	....	....	....	....	1690	....	....	....
	0–8	2.60		1.07	....	1620	....	....	....	....	1610	....	....	....	....	1680	....	....	....
	0–4	3.10		1.00	....	1990	....	....	....	....	1770	....	....	....	....	1940	....	....	....
	0–⅜	4.50		0.83	....	1690	....	....	....	....	1380	....	....	....	....	1490	....	....	....
	0–¾	5.40		0.77	....	1390	....	....	....	....	1060	....	....	....	....	1170	....	....	....
	0–1½	5.80		0.73	1910	1630	1300	1540	1010	1580	1300	1020	1170	830	1700	1410	1130	1450	900

TABLE 16—MODULUS OF ELASTICITY OF CONCRETE.

Values taken from the curves in Fig. 23 to 32 inclusive.

The average values for "Initial Tangent" Modulus are represented by the equation:

$$E_i = 40\,000\ S^{0.60}$$

For Tangent Modulus at 25 per cent Load:

$$E_{t25} = 84\,300\ S^{0.47}$$

In the above equation S is the Compressive Strength.

Data from Series.	For Details of Tests, see Table.	Modulus of Elasticity, 1000 lb. per sq. in. for Ultimate Strength (lb. per sq. in.).						
		500	1000	1500	2000	3000	4000	5000
		INITIAL TANGENT MODULUS (E_i).						
83	4	1600	2450	3150	3750	4800	5700	6600
89	5	2000	2800	3450	3950	4800	5550	....
93[a]	7	1400	2300	3000	3800	5200	6500	....
93	8	1400	2300	3100	3800	5100	6300	7400
104	13	2060	2840	3420	3890	4640	5300	6000
114	14	1700	2500	3150	3700	4800	5800	6870
Average.....		1690	2530	3210	3820	4890	5860	7000
		TANGENT MODULUS AT 25 PER CENT LOAD (E_t).						
99	12	....	....	2500	2750	3200	3500	....
104	13	1550	2130	2560	2920	3480	3970	....
114	14	1500	2280	2800	3200	3830	4330	4770
Average.....		1520	2200	2620	2920	3630	4350	4770

a Machine mixed.

TABLE 17—AVERAGE VALUES OF MODULUS OF ELASTICITY.

From Nomographic Chart Fig. 37.

K and n are factors in Eq. 1.

Compressive Strength, lb. per sq. in.	Value of K in 1000 lb. per sq. in.	Value of n.	Modulus of Elasticity, 1000 lb. per sq. in.									
			Initial Tangent.	For Different Percentages of Load.								
				Tangent Modulus.					Secant Modulus.				
				5	10	15	25	50	5	10	15	25	50
500	665	0.90	2100	1950	1720	1640	1550	1450	2170	1910	1820	1720	1610
1000	955	0.90	2900	2700	2380	2260	2140	2000	3000	2650	2510	2380	2220
1500	1200	0.90	3400	3160	2790	2650	2510	2350	3510	3160	2940	2790	2610
2000	1335	0.90	3900	3630	3200	3040	2890	2690	4040	3560	3380	3210	2990
3000	1674	0.90	4700	4370	3850	3670	3480	3240	4860	4280	4080	3870	3600
4000	1910	0.90	5300	4920	4350	4130	3920	3660	5470	4840	4600	4360	4070
5000	2186	0.90	5900	5500	4840	4600	4370	4070	6110	5380	5110	4860	4520

TABLE 18.—COMPARISON OF "EXPONENTIAL" AND "STRAIGHT-LINE" ANALYSIS.

For "Exponential" theory, steel stress assumed as 16 000 lb. per sq. in. in all cases.

Compressive Strength of Concrete, lb. per sq. in.	"Exponential" Theory.							"Straight-Line" Theory.				
	Fiber Stress in Concrete.		Value of				Resisting Moment, $\frac{M}{bd^2}$	Value of			Stress, lb. per sq. in.	
	Per cent of Ultimate Strength.	lb. per sq. in.	(n)[a]	(p)	(k)	(j)		(n)[b]	(k)	(j)	Steel.	Concrete.
500	10	50	15.7	.00007	.047	.985	1.2	60	.092	.970	16 200	25
"	25	125	17.4	.00049	.120	.959	7.5	"	.215	.928	16 500	76
"	50	250	18.6	.00189	.227	.922	27.6	"	.373	.876	16 800	170
1000	10	100	11.3	.00022	.066	.977	3.4	30	.108	.964	16 200	65
"	25	250	12.6	.00135	.164	.943	20.4	"	.247	.918	16 400	180
"	50	500	13.5	.00487	.297	.898	70.5	"	.414	.862	16 700	392
1500	10	150	9.5	.00041	.082	.972	6.3	20	.120	.960	16 200	110
"	25	375	10.8	.00246	.200	.931	36.7	"	.269	.910	16 350	301
"	50	750	11.5	.00865	.350	.879	121.5	"	.440	.853	16 500	648
2000	10	200	8.4	.00062	.095	.967	9.7	15	.128	.957	16 150	158
"	25	500	9.4	.00374	.227	.921	55.4	"	.283	.906	16 250	430
"	50	1000	10.0	.01266	.385	.867	175.0	"	.455	.848	16 400	908
2500	10	250	7.6	.00086	.105	.964	13.4	12	.134	.955	16 100	208
"	25	625	8.5	.00515	.250	.914	75.2	"	.293	.902	16 200	560
"	50	1250	9.1	.01706	.415	.857	234.0	"	.467	.842	16 300	1185
3000	10	300	7.0	.00115	.116	.960	17.7	10	.140	.953	16 100	263
"	25	750	7.8	.00662	.268	.907	95.6	"	.304	.899	16 150	705
"	50	1500	8.3	.02176	.429	.852	294.0	"	.477	.841	16 200	1445
3500	10	350	6.6	.00145	.126	.956	22.2	8.6	.146	.951	16 080	319
"	25	875	7.3	.00820	.286	.901	118.8	"	.311	.896	16 090	851
"	50	1750	7.8	.02660	.461	.840	357.0	"	.485	.838	16 090	1750

a Ratio of modulus of elasticity of steel to that of concrete. See secant modulus in Table 17.

b Based on Final Report of the Joint Committee on Concrete and Reinforced Concrete, Proc. Am. Soc. Testing Mat. Part I, 1917.

APPENDIX A[1]

FLEXURE OF REINFORCED CONCRETE BEAMS

By Stanton Walker.

Introduction.

In the foregoing paper values are reported for the modulus of elasticity of concrete made up of different proportions of cement and water, from aggregates of different grading, etc., and for tests made at different ages. No attention was given to the relation of these values to reinforced concrete design.

It is felt that it will be of value to point out certain features in the relation of these studies to the theory of flexure of reinforced concrete beams. The theory will be developed only for the case of the simple rectangular beam reinforced for tension. Reference to any good text book on reinforced concrete[2] will suggest to the reader methods of applying the theory to special cases, such as T-beams, slabs, columns, etc.

At the present time most designs are based on the assumption that the stress-deformation relation for concrete may be represented by a straight line below working stresses. This method is known to be an approximation, but is widely used because of its simplicity.

Prof. A. N. Talbot[3] and other writers have based their analysis of stresses in reinforced concrete beams on the assumption that the stress-deformation relation for concrete may be represented by a parabola having its vertex at the ultimate strength of the concrete. This analysis is recognized as being more nearly rational than the "straight-line" method. Its chief usefulness seems to be found in estimating the ultimate strength of reinforced concrete beams. The "parabolic" method is applicable to the design of beams for any working stress, but it is little used for this purpose due to the complex form of the equation representing the stress-deformation relation, and the difficulty of determining the constants involved.

Tests have shown that deformations in concrete are not directly proportional to the applied stresses, even for small ranges in stress or for low loads. A number of equations have been offered as representing the relation between deformation and stress in concrete. Probably the best known is the parabola mentioned above; however, the tests reported in the foregoing paper indicate that this relation may be more correctly represented by an equation of the form,

[1] This Appendix did not form a part of the original paper on "Modulus of Elasticity of Concrete."

[2] See, for example, "Principles of Reinforced Concrete Construction," by Turneaure and Maurer. "Concrete Engineers' Hand Book," by Hool and Johnson. "Reinforced Concrete Construction," Vol. 1, by Hool.

[3] See "Tests of Reinforced Concrete Beams," by A. N. Talbot, Bulletin 4, Univ. of Ill. Eng. Exp. Sta.

$$s = Kd^n \quad \text{.....(1) (See page 9.)}$$

Where s = unit compressive stress in concrete.
d = unit deformation of concrete,
K = a constant depending on the ultimate strength of the concrete,
n = an exponent, approximately constant.

It should be noted here that our tests show this equation to be true for loads up to 50 to 90 per cent of the ultimate strength of the concrete. It should not be used in the flexure formulas for stresses higher than about 50 per cent of the ultimate strength. This will answer for all practical problems of design.

The steps taken in arriving at a rational analysis of the direct stresses in a reinforced concrete beam may be summarized as follows:

(1) Determine the average compressive stress in terms of the stress at the outermost fiber.

(2) Determine the average tensile stress; (f_s if all of the tensile stress is assumed to be carried by the steel).

(3) Determine the position of the line of action of the average (or resultant) compressive stress.

(4) Determine the position of the line of action of the resultant tensile stress (horizontal gravity axis of steel).

(5) Determine the position of the neutral plane of the beam—the plane marking the boundary where compressive stresses leave off and tensile stresses begin.

ASSUMPTIONS.

The development of the design formulas given below is based on the following assumptions:

(1) The stress-deformation relation for concrete in compression is correctly expressed by an exponential equation. (Eq. 1.)

(2) Plane sections before bending remain plane after bending.

(3) All tensile stresses are carried by the steel.

(4) The concrete and steel stretch together.

(5) The neutral plane is perpendicular to the plane of applied load.

(6) No initial stress in the concrete.

Stress-Deformation Relation for Concrete.—The accuracy of any analysis of reinforced concrete beams depends largely upon the correctness with which the stress-deformation relation for the concrete has been determined. In view of the results of thousands of determinations of modulus of elasticity of concrete made at this Laboratory, it is felt that a more nearly rational design can be made by the use of the relations brought out by these tests. The theory which is developed below has the following distinct advantages:

(1) It takes into account a more nearly correct stress-deformation relation than is used in most other analyses.

(2) The formulas are no more complex than those used in the "straight-line" analysis.

Perhaps it is well to repeat at this point that some thirty years ago Bach[1] used an equation similar to our Eq. 1 to represent the stress-*elastic*-deformation relation for concrete. Mörsch[2] applies Bach's equation to the theory of flexure of reinforced concrete beams, but it is felt that the formulas developed by him are more complicated than necessary.

Certain engineers have objected to the acceptance of this equation to represent the stress-deformation relation for concrete because the curve represented by it becomes tangent to the stress axis. As stated in the foregoing paper, it is impossible with available instruments to obtain data for the very low loads—below say about 50 lb. per sq. in. However, it would seem that the question as to whether or not this tangency really occurs in the true relation is of minor importance. Our tests, as well as others, show this law to be true for any range of loads in which we are likely to be interested. We have proven to our own satisfaction that the initial curvature for low measurable stresses is not due to instrumental error, as has been suggested by certain of our critics.

If our equation is in error for stresses lower than those for which we are able to measure deformations satisfactorily, the inaccuracy introduced into the flexure formulas is so small that it is negligible.

Conservation of Plane Section.—In the development of equations for flexure of beams, homogeneous or otherwise, the assumption is made that sections which were plane before bending remain plane after bending. This assumption is known to be irreconcilable with the existence of shearing deformations. However, it probably introduces little error. Its use is made particularly imperative in reinforced concrete design due to the lack of information on the shearing modulus of elasticity.

Tensile Stress Carried by Steel.—For working loads in a properly designed reinforced concrete beam the concrete will have ceased to exert an appreciable resistance to tension at sections of any considerable bending moment some time before the steel is stressed to its working load. Since for direct stresses we are chiefly interested in the sections of maximum bending moment, this assumption should introduce little error.

Adhesion of Steel to Concrete.—The assumption that the concrete and steel stretch together supposes a perfect bond between the two materials. This is undoubtedly not the case, especially at the section of maximum bending moment. Tests on reinforced concrete beams made at the University of Illinois[3] showed a distinct difference in the deformation of the steel and the adjacent concrete. At the section of maximum bending moment the steel deformation is less than that of the concrete. At present it is not clear how this relation can be taken into account in deriving a simple formula for reinforced concrete design.

[1] "Elasticität und Festigkeit," by Carl von Bach (4th Edition, 1902).
[2] "Concrete-Steel Construction," (Der Eisenbetonbau), by Mörsch—Translation by E. P. Goodrich
[3] See "Tests of Bond between Concrete and Steel," by Duff A. Abrams, Bulletin 71, Univ. of Ill. Eng. Exp. Sta.

Neutral Plane Perpendicular to Line of Applied Load.—In design of beams for most purposes we are interested in cases where the load is applied perpendicular to the beam. Calculations for special loadings are not within the scope of this paper.

NOTATION.

In so far as consistent, the standard notation recommended by the Joint Committee[1] on Concrete and Reinforced Concrete will be used. At the time the paper on "Modulus of Elasticity of Concrete" was written for presentation to the American Society for Testing Materials the standard notation was not followed. However, no confusion should arise if attendant duplications are pointed out. It will be noted that in accordance with the following notation, s in Equation 1 is changed to f_c, d to e_c, and n to r.

Standard Notation[2].

f_s = tensile unit stress in longitudinal reinforcement.

f_c = compressive unit stress in extreme fiber of concrete. (See s in Eq. 1.)

E_s = modulus of elasticity of steel in tension.

E_c = modulus of elasticity of concrete in compression. In this appendix used as the secant modulus (E_s in Eq. 6) where the exponential stress-deformation relation is involved.

$n = \frac{E_s}{E_c}$ = ratio of modulus of elasticity of steel to that of concrete.

M = bending moment or moment of resistance in general.

A_s = effective cross-sectional area of metal reinforcement.

b = width of beam.

d = depth of beam to center of longitudinal metal reinforcement (effective depth).

k = ratio of depth of neutral axis to depth d.

z = depth from compression surface to resultant of compressive stresses.

j = ratio of lever arm of resisting couple to depth d.

$jd = d - z$ = arm of resisting couple.

p = ratio of effective area of tension reinforcement to effective area of concrete $= \frac{A_s}{bd}$.

Terms not given in Standard Notation.

e_s = unit deformation in steel.

e_c = unit deformation in concrete. (Same as d in Eq. 1.)

r = an exponent. (Same as n in Eq. 1.)

K = a constant.

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[1] See Proc. Am. Soc. Testing Mat., v. 21, 1921.

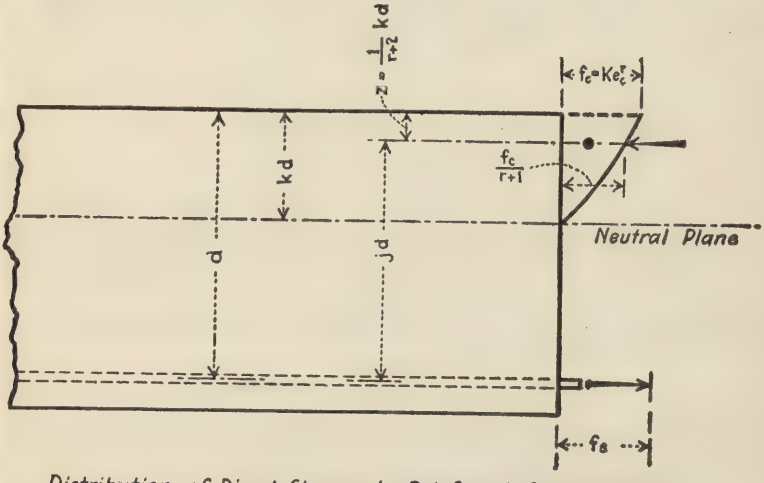
[2] (Note to Revised Edition.) In revising this Bulletin, the wording of the standard notation of the Joint Committee has been revised from that used in 1917 to conform with the Progress Report of the Joint Committee on Standard Specifications for Concrete and Reinforced Concrete; 1921.

FORMULAS FOR FLEXURE OF REINFORCED CONCRETE BEAMS.

Following the above notation Eq. 1 (see page 9) becomes

$$f_c = K e_c^r \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (18)$$

Let Fig. 38 represent the distribution of direct stresses at any cross-section in a rectangular reinforced concrete beam which is subjected to bending. Since the deformations are assumed to be proportional to the distance from the neutral axis, the curve representing the compressive stresses has an equation of the form of Eq. 18. It will be noted that this curve becomes tangent to the neutral plane.



Distribution of Direct Stresses in Reinforced Concrete Beam.

FIG. 38.

In deriving formulas for the position of the neutral plane it is necessary to know the average compressive stress in the concrete in terms of the maximum fiber stress. Basing the variation in stress on Eq. 18 it can readily be shown that

$$\frac{f_c}{r+1} = \text{average compressive stress} \quad \ldots\ldots\ldots\ldots (19)$$

Therefore the total compressive stress equals the average compressive stress multiplied by the stressed area, or

$$\Sigma f_c = \frac{f_c}{r+1} kdb \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (20)$$

For the sake of the ultimate simplicity of the formulas the slope of a secant to the fiber stress will be used as the measure of the modulus of elasticity of the concrete. (Ratio of stress to deformation at the outermost fiber.) The use of this quantity introduces no further approximation.

Eq. 20 may then be written,

$$\Sigma f_c = \frac{E_c e_c}{r+1} kdb \quad \ldots\ldots (21)$$

(See Eq. 6, page 13. Note that in accordance with the changes in notation mentioned above E_c is the same as E_s in Eq. 6 and e_c the same as d in the same equation.)

Assuming all the tensile stress to be carried by the steel, the total tension is

$$\Sigma f_s = A_s f_s = A_s E_s e_s \quad \ldots\ldots (22)$$

Since for equilibrium the total tension equals the total compression ($\Sigma f_c = \Sigma f_s$)

$$A_s E_s e_s = \frac{E_c e_c}{r+1} kdb \quad \ldots\ldots (23)$$

Assuming the conservation of plane sections;

$$\frac{e_s}{1-k} = \frac{e_c}{k} \quad \ldots\ldots (24)$$

By definition

$$\frac{E_s}{E_c} = n, \text{ and } \frac{A_s}{bd} = p.$$

Substituting the values for n and p from the above equations in (23) and dividing by Eq. 24, we obtain

$$n\,(1-k) = \frac{k^2}{(r+1)\,p} \quad \ldots\ldots (25)$$

Solving this quadratic, the ratio of the depth of the neutral axis to the effective depth of the beam may be expressed as

$$k = \sqrt{(r+1)pn + \left(\frac{r+1}{2}pn\right)^2} - \frac{r+1}{2}pn \quad \ldots\ldots (26)$$

For problems of design (where the concrete and steel stresses are assumed) Eq. 26 may be written in a simpler form

$$k = \frac{1}{1+\frac{f_s}{nf_c}} \quad \ldots\ldots (27)$$

(Note, let

$$\frac{f_c}{r+1} kdb = A_s f_s = pbdf_s,$$

substitute

$$\frac{1}{(r+1)\frac{f_s}{f_c}\left(\frac{f_s}{nf_c}+1\right)}$$

for p, and solve for k. See Eq. 20, 22 and 36.)

In order to determine the moment arm (jd) of the resisting couple it is necessary to know the position of the line of action of the resultant compressive stress. The distance of this line below the top of the beam will be equal to the distance from the top of the beam of the centroid of the area representing the compressive stresses. (See Fig. 38.) By application of the calculus it can easily be shown that this distance equals

$$z=\frac{1}{r+2}kd \quad \ldots\ldots (28)$$

Since d is taken as the distance from the top of the beam to the center of the steel, the moment arm of the resisting couple is

$$jd=d-z=d-\frac{1}{r+2}kd \quad \ldots\ldots (29)$$

Then

$$j=1-\frac{1}{r+2}k \quad \ldots\ldots (30)$$

The moment of the resisting couple may be expressed either as the product of the summation of the tensile stresses and the moment arm, or as the product of the summation of the compressive stresses and the moment arm.

Therefore,

$$M=f_sA_sjd \quad \ldots\ldots (31)$$

$$=\frac{f_c}{r+1}kdbjd \quad \ldots\ldots (32)$$

Substituting pbd for A_s in Eq. 31 and solving for f_s, we obtain

$$f_s=\frac{M}{pjbd^2} \quad \ldots\ldots (33)$$

Substituting the value of M found in Eq. 31 and 33 in 32 and solving for f_c we obtain

$$f_c=\frac{(r+1)\,p\,f_s}{k} \quad \ldots\ldots (34)$$

Solving for f_c in Eq. 27, the following expression may be obtained for the concrete fiber stress,

$$f_c=\frac{kf_s}{n(1-k)} \quad \ldots\ldots (35)$$

From preceding equations it can be shown that the steel ratio (p) for balanced reinforcing equals

$$p=\frac{1}{(r+1)\frac{f_s}{f_c}\left(\frac{f_s}{nf_c}+1\right)}=\frac{f_ck}{(r+1)f_s} \quad \ldots\ldots (36)$$

It was stated above that the equations resulting from the application of the stress-deformation relation for concrete expressed by Eq. 1 (same as

Eq. 18) are no more complicated than those used in the "straight-line" analysis. An examination of Eq. 18 shows that it represents a straight line when r equals 1. If 1 is substituted for r in any of the above equations the formulas used in the "straight-line" analysis will be obtained. It will, therefore, be seen that so far as the forms of the equations are concerned the only difference is that in many cases the quantity $\frac{r+1}{2}$ is used where 1 occurs in the "straight-line" formula, etc. Most of the dependent equations are unchanged. An examination of the data contained in the paper on Modulus of Elasticity shows that r (same as n in the text) is approximately constant for all concrete. The designer may, therefore, write into his equations what he considers an average value of r (about 0.9 may be considered average) and obtain formulas equal in simplicity to the usual straight-line equations.

DISCUSSION OF FORMULAS.

A comparison of the results obtained from the "exponential" formulas, and from the "straight-line" formulas should be of interest. For convenience formulas for both of these methods are summarized below:

DESIGN FORMULAS FOR REINFORCED CONCRETE.

Variable.	"Exponential" Theory.		"Straight-Line" Theory.	
	Formula.	Equation No.	Formula.	Equation No.
k	$\sqrt{(r+1)pn+\left(\frac{r+1}{2}pn\right)^2}-\left(\frac{r+1}{2}\right)pn$	(26)	$\sqrt{2pn+(pn)^2}-pn$	(37)
k	$\frac{1}{1+\left(\frac{f_s}{nf_c}\right)}$	(27)	$\frac{1}{1+\left(\frac{f_s}{nf_c}\right)}$	(38)
j	$1-\left(\frac{1}{r+2}\right)k$	(30)	$1-1/3k$	(39)
p	$\frac{1}{(r+1)\frac{f_s}{f_c}\left(\frac{f_s}{nf_c}+1\right)}$	(36)	$\frac{1}{2\frac{f_s}{f_c}\left(\frac{f_s}{nf_c}+1\right)}$	(40)
p	$\frac{f_c k}{(r+1)f_s}$	(36)	$\frac{f_c k}{2f_s}$	(41)
f_s	$\frac{M}{pjbd^2}$	(33)	$\frac{M}{pjbd^2}$	(42)
f_c	$\frac{(r+1)pf_s}{k}$	(34)	$\frac{2pf_s}{k}$	(43)
f_c	$\frac{kf_s}{n(1-k)}$	(35)	$\frac{kf_s}{n(1-k)}$	(44)

The values of modulus of elasticity used in the "straight-line" formulas are little more than emperical coefficients, which have been found to give safe results. Reference to the table at the top of page 42 will show that the

values of modulus of elasticity recommended by the Joint Committee are lower than those obtained from our tests. They are also lower than the values suggested by Schüle. Taylor and Thompson, Falk and other writers.

Since our formulas are based on the stress-deformation relation obtained from actual tests it would seem proper in comparing the "exponential" and "straight-line" formulas to use the moduli of elasticity obtained from our tests in the former and those recommended by the Joint Committee in the latter.

In Table 18 the resisting moment (in terms of the dimensions of the beam), the percentage of steel, etc., are calculated for given concrete and steel stresses using the "exponential" formulas. The stresses in the concrete and steel are then determined by the "straight-line" formulas for the same resisting moments and the same percentages of steel.

Consider, for example, the concrete having an ultimate strength of 2500 lb. per sq. in. at 28 days. Determine the percentage of steel and the resisting moment for the concrete stressed to one-quarter of its ultimate load (625 lb. per sq. in.) and the steel stressed to 16 000 lb. per sq. in. From Table 17 the value of n for 2500-lb. concrete stressed to $\frac{1}{4}$ load is found to be 8.5 if the modulus of elasticity of the steel is taken as 30 000 000 lb. per sq. in. For all of these tests the average r was 0.9. Then the percentage of steel required by the above stresses may be calculated directly from the second member of Eq. 36; or k may first be calculated from Eq. 27 and p calculated from the last member of Eq. 36. From the above $p = .00515$ and $k = .250$. Then from Eq. 30, $j = .914$. Since we are not interested in the dimensions of the beam, the resisting moment will be calculated in terms of bd^2. Then from Eq. 33

$M = 75.2\ bd^2$ (in. lb. when the dimensions of the beam are in inches.)

Now let us calculate the stresses in the concrete and steel for the same beam with the same load by means of the "straight-line" formulas. The bending moment, the percentage of steel and the ultimate strength of the concrete will, of course, remain unchanged. For concrete of this strength the Joint Committee recommend $n = 12$. The value of k and j may be calculated from Eq. 37 and 39. They are $k = .293$ and $j = .902$, respectively. Then from Eq. 42 and 43 the steel and concrete stresses are found to be 16 200 and 560 lb. per sq. in., respectively. It is seen that if the values of n from our tests are used for the "exponential" formulas and the Joint Committee values are used for the "straight-line" formulas, for a given factor of safety in the concrete, a somewhat safer design is given by the former than by the latter, since the steel stresses are only about 1 per cent higher for the second method and the concrete stresses are 10 per cent lower. It will be noted from the table that the percentage difference becomes less as loads nearer the ultimate strength are assumed and as stronger concrete is used.

Let us now find the concrete stresses by the "straight-line" method using the same value of n as that used in the "exponential" formulas. n was

found to be 8.5; then for $p = .00515$, $k = .254$ and $j = .915$. From Eq. 42 the steel stress is found to be 16 000 lb. per sq. in. and the concrete stress 660 lb. per sq. in. Or within slide rule accuracy the steel stress is unchanged and the concrete stress is 5 per cent higher than that given by the "exponential" equation. In other words, using the same value of n in each case for ordinary concrete, the "straight-line" formulas give a slightly more conservative design.

APPENDIX B.

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Bulletin 6

Structural Materials Research Laboratory
Lewis Institute
Chicago

Effect of Storage of Cement

By

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Professor in Charge of Laboratory

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FOREWORD TO SECOND EDITION

This report was originally printed in the Minutes of the Spring Meeting of the Portland Cement Association, April, 1920 and was reprinted as Bulletin 6 in June, 1920.

In the second edition the text has been entirely rewritten; the tables have been revised to include tests for the 2 and 5-yr. storage periods. The summary tables (10 to 13) have been rearranged; all figures have been redrawn.

No important changes in the original conclusions have been made necessary by the addition of the later tests.

The principal conclusions from a preliminary study of the data from an investigation of bin-stored cements are included.

A comprehensive bibliography on storage of cement has been added.

EFFECT OF STORAGE OF CEMENT

By Duff A. Abrams

SUMMARY

Tests were made in order to determine the concrete and mortar-making properties of 3 different lots of portland cement which had been stored up to 5 yr. in sacks under different conditions. The cements were purchased from dealers' warehouses and stored in the Testing Laboratory, in the basement of Lewis Institute, and in a shed in the yard for 2 yr. After 2 yr. all cements were stored in the Laboratory. In general the cement was stored in lots of 800 to 1200 lb. in standard cotton sacks; in one group of tests 2 brands of paper sacks were also used; in another group the cloth sacks were covered with thin layers of hydrated lime and portland cement. Upon receipt of the cement, and after storage for 3 mo., 6 mo., 1, 2 and 5 yr., concrete and mortar specimens were made for test at ages of 7 and 28 days, 6 mo., and 1 and 2 yr. The tests were begun November, 1916, and completed November, 1923.

This report includes compression tests of about 1250 6 by 12-in. concrete cylinders, 1300 2 by 4-in. cylinders of 1:3 standard-sand mortar, and about 500 miscellaneous tests.

The following are the principal conclusions from this investigation:

1. The average strength of the concrete (mix, 1:5 by volume, relative consistency 1.00 tested in 6 by 12-in. cylinders, cured in a damp condition) made from the cement as received was 1470 lb. per sq. in. at 7 days; 3020 at 28 days; 4410 at 3 mo.; 4680 at 1 yr.; 4910 at 2 yr.; and 6030 at 5 yr. The increase in strength of concrete with age shown by these tests was approximately proportional to the logarithm of the age, which is characteristic of concrete cured in a damp place.

2. There was an appreciable loss in strength of portland cement due to storage in small lots in sacks for all conditions covered by these tests; the loss was greatest for the cements stored in the shed, and least for those stored in the Laboratory. Basement storage was almost as severe as outdoors. The loss in strength was greater for the first 3 mo. of storage than for later 3-mo. periods. For example, the 28-day tests for cement stored in shed showed a loss of about 500 lb. per sq. in. for the first 3-mo. storage and about 250 lb. for the second 3 mo. Still smaller losses were found for later 3-mo. periods. In general the concrete strengths for the cements stored in the shed 1 yr. and longer were about 80 per cent of those for cement stored in the Laboratory. The deterioration shown by these tests was probably greater than would be found in a larger lot of cement stored in sacks under similar conditions.*

*Tests on bin-stored cement now under way have shown an increase in concrete and mortar strength for 4-mo. storage particularly in the 7 and 28-day tests; beyond this time a *decrease* was found, but up to 1½-yr. storage the strength of the cement had not, in general, decreased below that obtained in the initial tests, which were made only a few days after grinding the cement.

3. The effect of storage of cement was found to be largely a question of the *age at which concrete or mortar tests were made.* The early tests showed a much greater loss in strength due to storage of cement than tests at later ages. It is of the utmost importance that the strength of the cement was not *permanently* reduced as shown by the early tests; cements stored in shed for 3 mo. gave an average "strength-ratio" of 73 per cent (as compared to the original strength of concrete) when tested at 7 days, 75 per cent at 28 days, and 84 per cent when tested at 6 mo. to 2 yr. Similar relations were found for the other conditions of storage. (See Table 10 and Fig. 3.)

4. After storage of cement in shed for 3 mo. the average strength-ratio for the ages at which tests were made was 80 per cent; after storage for 6 mo., 72 per cent; 1 yr. 60 per cent; 2 yr., 46 per cent; and 4½ yr. 45 per cent. (See Table 10 and 11 and Fig. 3.)

5. Two brands of paper cement sacks gave results which did not differ materially from cloth sacks when used for storing cement for periods up to 4½ yr. (See Table 12.)

6. A thin covering of portland cement or hydrated lime over cement in cloth sacks showed some advantage, but not sufficient to justify the cost of this method of storage. (Table 13.)

7. There was no essential discrepancy between the indications of the compression tests of 1-5 concrete in the form of 6 by 12-in. cylinders and the tests of 1:3 standard-sand mortar in 2 by 4-in. cylinders.

8. The time of setting of cement increased up to storage periods of 1 or 2 yr., and decreased for the longer periods. At the beginning of the tests the initial time of setting was about 4½ hr., after storage for 1 yr. about 7 hr.; for final time of setting the corresponding values were about 8 and 12 hr. (Table 2 and Fig. 11.)

9. The normal consistency of cement was only slightly affected by storage up to 2 yr.

10. It appears that the deterioration of cement in storage is due to absorption of atmospheric moisture, which causes a partial hydration, which in turn, exhibits itself in the lower strength-ratios for concrete, particularly at the early ages.

11. Only a negligible quantity of lumps formed up to 1-yr. storage; these were soft and readily broken. The lumps found in the sacks after storage for 2 yr. and over were generally quite hard; in the shed-stored cements lumps amounted to as much as 30 to 75 per cent of the cement. Lumps were generally discarded before testing the cement.

Concrete and mortar tests of cement and pulverized lumps from cement stored for 7 yr. showed the cement to have about 30 per cent of its normal strength and the lumps 35 per cent of the strength of the cement; in other words the "lump cement" gave 10 per cent of the original concrete strength. For these tests the lumps were pulverized to such a fineness that all passed a 28-mesh sieve and about 45 per cent was retained on a 200 sieve. Earlier tests of broken lumps screened from cement and tested shortly after it was received at the Laboratory gave strengths in concrete about 50 per cent of that made with cement from the same sacks.

EFFECT OF STORAGE OF CEMENT

By Duff A. Abrams.

Introduction

The effect of storage of portland cement is of interest to the manufacturer, dealer and user, due to the growing practice of delivering concrete materials on the job prior to the opening of the construction season. The purpose of this series of tests was to determine the effect of different conditions and periods of storage on the concrete and mortar-making qualities of portland cement, and to study the effect of certain methods for protecting cement in storage.

This report includes tests on three different lots of cement stored in sacks under different conditions. These tests were started in November, 1916, and completed in November, 1923. Each of the three samples used was a mixture of equal parts of four brands of portland cement purchased from warehouse stocks in Chicago. About 1250 6 by 12-in. concrete cylinders, and 1300 2 by 4-in. cylinders of 1:3 standard-sand mortar, and about 500 miscellaneous tests of cement were made.

Another series of tests is now under way, in a study of the effect of storage of cement in bulk in large quantities and in wood barrels and in cloth sacks under different conditions.

These investigations are a part of the experimental studies of concrete and concrete materials being carried out through the cooperation of Lewis Institute and the Portland Cement Association.

Outline of Investigations

The results of tests are given for three groups of samples of cement stored for periods up to 5 yr. Cement samples were stored in standard cotton sacks unless otherwise noted. The nature of the investigation will become clear from the following outline.

Cement 3705; storage began November, 1916.

(*a*) In Testing Laboratory, a large steam-heated room on the ground floor of Lewis Institute; temperature quite uniform; humidity low during winter.

(*b*) In basement of Lewis Institute; temperature 5 to 10°F. lower than (a); humidity higher at all times than (a). Cement removed to (a) after 2 yr.

(*c*) In shed near Laboratory; no artificial heat. The sacks were piled on the floor about 1 ft. above the ground. A roof and thin board walls protected the cement from direct contact with rain and snow, but allowed free circulation of outside air. The conditions here were similar to those in a temporary cement storage shed in the field. Cement removed to (a) after 2 yr.

(*d*) Stored in sacks in Laboratory 2 mo. before mixing and then in bulk in a metal-lined box in basement 1 mo. after mixing. Test specimens were made for this 3-mo. storage period only.

Cement 3827; storage began May, 1917.

(*a*) In Testing Laboratory; same as (a) above.
(*b*) In basement; same as (b) above.
(*c*) In shed; same as (c) above; cloth sacks.
(*e*) " " " " " "Jaite" paper sacks.
(*f*) " " " " " "Bemis" " "

Cement 3965; storage began November, 1917.

(*c*) In shed; same as (c) above.
(*g*) " " " " " hydrated lime between sacks.
(*h*) " " " " " portland cement " "

The manufacturers who donated the paper sacks for these tests described them as follows:

The Jaite Co., Boston, Ohio, "Puncture and waterproof paper cement bags."

Bemis Bros. Bag Co., Peoria, Ill., "Rope-paper cement sacks."

Eight to twelve sacks of cement were stored for each condition.

For Cement 3965, sacks were placed in a rough box, in tiers of 4 sacks each. A layer of cement or hydrated lime about ½ in. thick was sprinkled on the floor and on each layer of sacks. This required about 1 sack of cement or lime for 8 sacks of cement.

TESTS

Tests were made on each of the cements:

(1) When received (beginning of tests)
(2) After Storage for 3 mo.
(3) " " " 6 "
(4) " " " 1 yr.
(5) " " " 2 "
(6) " " " 5 "

The following tests were made on each of the cements at the expiration of each of the above-mentioned storage periods.

Concrete.

Mix. 1:5 by volume,
Compression tests of 6 by 12-in. cylinders at ages of 7 and 28 days, 6 mo., 1 and 2 yr.
Cylinders stored in damp sand until test; tested damp.

Mortar.

1:3 standard sand by weight,
Compression tests of 2 by 4-in. cylinders at ages of 7 and 28 days, 6 mo., 1 and 2 yr.
Cylinders stored in water until test; tested damp.

Miscellaneous Tests of Cement.

Normal consistency,
Soundness,
Fineness (when received only)
Time of setting,
Temperature changed during setting,
Determination of loss on ignition, moisture, and carbon dioxide.

Tests of lumps. Tests of concrete were made using pulverized cement lumps for the following conditions:

(1) Lumps screened from cement and tested in concrete shortly after it was received at the Laboratory. Tested at ages of 7 days to 2 mo. (Details of tests not reported.)

(2) A mixture of pulverized lumps and cement, recorded under 2 and 4-yr. storage period for cement 3965. (Table 8.)

(3) Cement and pulverized lumps from the three cements used in this investigation, after storage for 7 yr. (Details of tests not reported.)

MATERIALS AND TEST PIECES

Each of the cements used in these tests consisted of a mixture of equal parts of four brands of portland cement purchased from dealers' warehouses in Chicago. The cement was thoroughly mixed dry in a concrete mixer, one sack from each brand. Before making the tests the cements were screened through a No. 20 sieve; and in general lumps were rejected. In certain tests (mentioned above) the lumps were broken and used.

The concrete consisted of 1 part of cement to 5 parts by volume of mixed sand and pebbles graded up to 1¼ in. Aggregate was from Elgin, Ill., pit of the Chicago Gravel Co. In order that the grading might not vary over a long period, the sand and pebbles were separated into 8 different sizes and recombined in definite proportions for each batch; see Table 1.

The following quantities of materials were used in each cylinder:

Cement	3.80 lb.
Aggregate	27.00 "
Water (980 c. c.)	2.16 "

The mixing water was 7 per cent of the weight of the dry materials; or a water-ratio to volume of cement of 0.86. While the normal consistency of the cement varied slightly from time to time, these variations made only insignificant differences in the water requirements of the concrete, hence were disregarded.

Concrete batches were mixed by hand in a shallow pan. The concrete had a "relative consistency" of about 1.00. The workability was not measured; the slump and flow tests were developed and standardized after this series was begun; the exact consistency was unimportant, so long as it was uniform throughout the series.

Cement tests were made in accordance with the Standard Specifications and Tests for Portland Cement of the American Society for Testing Materials. Sufficient mortar was mixed in a batch for five 2 by 4-in. cylinders—one for test at each age.

Concrete and mortar cylinders were molded in steel forms. They remained in the forms for about 20 hr. Concrete was cured in damp sand or in moist room until day of test; mortar specimens in water. Specimens were tested damp.

TEST DATA

Tables 1 to 3 give miscellaneous data on aggregates and cement, and Tables 4, 6 and 8 the strengths of concrete and mortar. Each strength value is the average of 5 tests made on different days.

In Tables 5, 7 and 9 "strength-ratios" of the concrete and mortar tests in Tables 4, 6 and 8 are expressed as percentages of the strengths of the cement at the beginning of tests. These strength-ratios were obtained by: (1) platting the age-strength relation (similar to Fig. 10) for a given condition of storage; (2) drawing smooth curves; (3) tabulating the strengths from the curves for the ages shown; and (4) reducing these strengths to percentages of the strengths for the cement at the beginning of the tests. It will be seen that the strengh-ratios are not exactly the same as would have been obtained by *direct* use of the strengths. The method used serves to eliminate minor irregularities and indicates the *true trend* of the tests.

The following summaries are given of certain groups of tests:

Table 10—Summary of Strength Tests of 1:5 Concrete,
Table 11—Effect of Condition of Storage of Cement,
Table 12—Cloth *vs.* Paper Cement Sacks,
Table 13—Effect of Hydrated Lime and Portland Cement as Coverings for Cement Sacks.

In general these average values should be used for comparison only; they do not represent any specific condition, since the strength-ratios were different for each storage period and age at test.

Fig. 1 shows the rainfall, humidity and temperature during the time the cements were in storage. The curves show weekly averages from the "Monthly Meteorological Summary" of the Weather Bureau in Chicago.

Fig. 2 to 12 give the most significant results of the tests. Fig. 2 is typical of the relation between period of storage of cement and strength of concrete and mortar using the average strengths for the "shed-in-yard" storage for the 3 lots of cement; the same data expressed as strength-ratios are platted in Fig. 3. Similar curves may be drawn for other tests in Tables 4 to 9.

Fig. 4, 6 and 8 show the relation between the storage period of the cement and the strength-ratios for concrete. The strength-ratios are shown for each storage condition, but only average curves are drawn. Similar curves for compression tests of 1:3 standard-sand mortar are given in Fig. 5, 7 and 9.

Typical age-strength curves for 1:5 concrete made from cement stored in shed and in Testing Laboratory are shown in Fig. 10. Data from Table 10. Similar curves may be drawn from the data in Tables 4, 6 and 8. Diagrams of this type formed the basis for calculation of the strength-ratio.

The relation between period of storage and time of setting of cement is given in Fig. 11. The results of the miscellaneous chemical tests are shown in Fig. 12.

DISCUSSION OF TESTS

The samples stored in the Laboratory (a) were under about the most favorable conditions practicable in this latitude, for cement stored in sacks. Those in the shed-in-yard (c) were under conditions which would be considered good for cement stored in cloth sacks on construction work. The basement storage (b) was intermediate between (a) and (c) so far as humidity was concerned. The use of paper sacks and coverings of cement or hydrated lime were variations of the shed storage.

In the following discussions the strength of the cement after stor-

age is expressed in terms of the strength-ratio, or the percentages of the strength of the cement at a given age and for a given condition of storage as compared with its strength when received. The average normal strengths of the cement in 1:5 concrete of a relative consistency of 1.00, used for purposes of comparison, are shown in Fig. 2 and 10 and Table 10. The compressive strengths of 6 by 12-in. concrete cylinders, cured in damp sand until test was 1470 lbs. per sq. in. at 7 days; 3020 at 28 days; 4410 at 6 mo.; 4680 at 1 yr.; 4910 at 2 yr.; and 6030 at 5 yr. The increase in strength of concrete with age shown by these tests is approximately proportional to the logarithm of the age and is characteristic of concrete cured in a damp place.

It is of the utmost importance to distinguish between the period of cement storage and the *age at test* of concrete and mortar.

There was no essential discrepancy between the indications of the compression tests of 1:5 concrete in the form of 6 by 12-in. cylinders and the tests of 1:3 standard sand mortar in 2 by 4-in. cylinders.

The compression tests of concrete and mortar showed a progressive deterioration in strength of the cement with continued storage. The effect of storing cements under different conditions for periods up to 4½ yr. is given in Tables 10 and 11. The strength-ratios in Table 10 are the average for the different storage conditions in Tables 5, 7 and 9. Table 11 gives the averages for all ages at test.

The loss in strength was greatest for the cements stored in the shed, and least for those stored in the Laboratory. The basement storage was almost as severe as outdoors.

Cement stored in shed (c) gave an average strength-ratio for the ages at which the tests were made of 80 per cent after 3 mo. storage; 72 per cent after 6 mo.; 60 per cent after 1 yr.; 46 per cent after 2 yr.; and 45 per cent after 4½ yr.; other storage conditions showed a similar relation with time of storage.

In general cement could be stored twice as long in the Laboratory as in shed for the same reductions in strength. The condition of storage in the basement was only slightly better than that in the shed. Deterioration was probably greater in these tests than would be found in a large lot of cement stored under similar conditions.

Another series of tests not included in this report, for which cement was received from a mill in Eastern Pennsylvania within a few days after grinding, showed increases in concrete and mortar strengths for periods of storage up to about 4 mo., particularly for the earlier ages at test; after 4-mo. storage there was a decrease in strength.

The later tests do not conflict with the data in this Bulletin, since there was a difference in the "zero" storage period for the cements in the two investigations. In the earlier series the cement was probably 2 to 4 mo. old before the first tests were made, hence if an increase in strength had occurred, the tests would not have shown it.

In the above-mentioned tests on bin-stored cements, parallel tests have been made on the same cement stored up to 1½ yr. under the following conditions:

(1) In cloth sacks outdoors under tarpaulin in Eastern Pennsylvania,
(2) At Lewis Institute in wood barrels in shed,
(3) " " " " cloth sacks in shed,
(4) " " " " cloth sacks in basement,
(5) " " " " air tight cans.

The strength of the cement from the mill bin and from air-tight cans had not in general decreased below that obtained at the beginning of the tests. The cement stored in wood barrels up to 9 mo. gave only slightly lower strengths than that from the mill bin. After 1 and 1½-yr. storage the strength of the cement in barrels was about 90 per cent of that from the mill bin. Cement stored for 1 and 1½ yr. in sacks in the same shed as the barrels gave strengths about 75 per cent of those for the barrels and 68 per cent of those for the bin storage. Approximately the same results were obtained for the cement stored in sacks in the basement of the Laboratory, in the shed, and outdoors under tarpaulin. These tests are being continued for longer periods of storage.

The effect of storage of cement on the strength of concrete and mortar is largely a question of the *age of the specimens at test.* The loss in strength due to storage became less apparent as the age of the concrete or mortar increased.

Fig. 2 and 3 and Table 10 show at different ages of test the effect of storing cement in shed. The average strength of 1:5 concrete made from cement stored for 6 mo., as shown in Table 10, was 66 per cent of the original strength for the 7-day tests, 69 per cent at 28 days, and 76 per cent at 6 mo. Beyond 6 mo. there was little change in the strength-ratios.

The same tendency is shown even after storing the cement up to 5 yr. Cements 3705 and 3827 stored in the Laboratory 4½ and 5 yr. gave strength-ratios of 43 per cent, 53 per cent, 62 per cent, 61 per cent and 61 per cent when tested in concrete at ages of 7 days to 2 yr.

It is of utmost importance that the strength of cement was not permanently reduced as shown by the early tests.

There was no marked difference in the quality of cement stored in cloth or in paper sacks up to 4½ yr. The 2 brands of paper sacks gave almost identical results, as shown in Table 12. The average strength-ratio of cement stored in cloth sacks for all test ages was 54 per cent; for "Jaite" paper sacks 57 per cent; and for "Bemis" paper sacks 55 per cent.

The tests on the use of portland cement and hydrated lime as coverings for cloth sacks showed only a slight advantage for this form of protection. The average of the concrete and mortar cylinders tested up to 2 yr. of age are given in Table 13. The average strength-ratio of cement stored in cloth sacks uncovered (for periods of 3 mo. to 4 yr.), was 61 per cent; for sacks covered with hydrated lime, 67 per cent; and for sacks covered with portland cement, 65 per cent. There seems to be little room for choice between cement and lime for this purpose. The small benefit obtained by these methods of protection does not justify the cost.

The *storage period* of the cement and the *age at test* of the concrete or mortar appear to be of greater importance than the exact condition of storage, so long as the cement is protected from direct contact with moisture.

The normal consistency of the cement, as determined by the Vicat needle, was only slightly affected by storage. For cements stored 1 and 2 yr. the normal consistency was in some instances increased from about 23 to 24 or 25 per cent and in one instance at 4½ yr. to 28.5 per cent.

Storage of cement had the effect of increasing both the initial and final time of setting 50 to 100 per cent up to the 2-yr. storage. After 5-yr. storage, however, the time of setting had decreased to about the value when received. See Fig. 11.

In the standard test for soundness (over boiling water) all cements were sound at all storage periods covered by these tests.

The deterioration of cement in storage appears to be due to the absorption of atmospheric moisture, causing partial hydration which exhibits itself in reducing the strength of the concrete. The principal reason for the greater reduction in strength due to storage in the shed than in the Laboratory was undoubtedly due to the higher moisture content of the air. This conclusion is substantiated by a comparison of the chemical analyses of Cement 3965 in Table 3 and the result of the strength tests of this cement at the 2 and 4-yr. storage periods. (See Table 8.) This cement was stored in the shed for 2 yr. and thereafter in the Laboratory. The average moisture content of the 3 lots after 4-yr. storage was 0.67 per cent as compared with 1.37 per cent at 2 yr. and shows that the cement gave up moisture after removal to the Laboratory. Table 8 shows little decrease and in many instances an increase in strength at 4 yr. as compared with 2 yr.

The average relative humidity in Chicago is about 70 per cent; this represents the condition for the shed storage. The humidities in the Laboratory and basement were about 25 and 40 per cent, respectively, in the winter, and about 55 and 70 per cent in the summer.

LUMPS IN STORED CEMENT

The exact method of dealing with lumps in stored cements was a complicating feature of the tests. In the earlier samples all lumps coarser than No. 20 sieve were rejected before the cements were tested. No lumps, or only soft and readily-broken lumps, were found in the cements which had been stored less than 1 yr. Cement 3705 placed in the shed in the fall showed about 8 per cent of lumps coarser than the No. 20 sieve after 1 and 2-yr. storage.

Cement 3965 stored in shed in the fall gave about 12 per cent of lumps after storage of 1 yr. and 30 to 75 per cent of lumps after 2 yr. The lumps after 2-yr. storage period were broken on the concrete floor with a metal tamper, mixed with the cement, and used in the concrete. The tests in Table 8 show that even in this condition the cement had considerable strength.

Another group of concrete tests (not reported in detail) in which lumps screened from Cement 3965 at the time it was placed in storage were used, showed a strength when tested in concrete at 7 days of 43 per cent of the *cement from the same lot;* 51 per cent at 28 days; and 57 per cent at 2 mo. These values are approximately the same as obtained for the 2-yr. storage of Cement 3965, which contained large quantities of lumps.

Another group of tests was carried out on cement and pulverized lumps after 7-yr. storage of the 3 lots of cement used in this investigation. The average fineness of the *cement* was about 22 per cent on the 200-mesh sieve. Lumps from the cement collected during the major investigation were pulverized on a concrete floor by means of a metal tamper and roller to such a fineness that all passed the 28-mesh

sieve and about 45 per cent remained on the 200-mesh sieve. The principal results were as follows:

(1) The lumps had strengths in concrete and mortar at 7 days about 35 per cent of the *cement* from the same sacks; the cement had only about 30 per cent of its original strength.

(2) The time of setting of both the cement and pulverized cement lumps was less than for the cement at 5 yr. and was 30 to 50 per cent of the normal time of setting. One sample of lumps which had set in an unusually hard mass, after being pulverized, showed a final time of setting of less than 1 hr.

A group of tests on a small sample of portland cement which had been stored in the mountains of Northern Mexico for 12 yr. are of interest in this connection. In 1:5 concrete this cement gave the following compressive strengths:

7 days— 340 lb. per sq. in.
28 " — 940 " " " "
3 mo. —1700 " " " "

STORAGE OF CEMENT ON THE WORK

Cement in temporary storage houses should be piled 1 ft. or more from the ground and exterior walls to prevent contact with moisture.

The following extracts from recent State Highway Specifications covering concrete road construction show current practice in storing cement on the job:

"The cement shall be stored in such a manner as to permit easy access for suitable inspection and identification of each shipment, and in a suitable weather-tight building which will protect the cement from dampness. When permission is given to store in the open, a platform and ample water-proof covering shall be provided as directed." (Pennsylvania, 1922.)

"Cement stored by the contractor for longer than 2 months must be held for retest. If the cement has lost strength during the period of storage, as shown by the tests of this department, sufficient additional cement must be added * * * to overcome such loss." (Washington, 1922.)

"It is understood and agreed that the Contractor shall store, prior to July 1, 1923, at his entire expense and in a manner satisfactory to the Chief Highway Engineer, not less than thirty-three and one-third (33⅓) per cent of the total amount of cement needed to complete this section." (Illinois, 1923.)

BULK CEMENT

The practice of shipping cement in bulk is becoming more common. Bulk cement offers many advantages on work where the conditions are suitable.

The tests of bin-stored cements now under way in this Laboratory show that practically no deterioration in strength had occurred up to 1½-yr. storage in mill bin, whereas tests of the same cement stored in shed and in basement gave strength-ratios of about 70 per cent after the same period of storage.

CONCLUDING REMARKS

The cements used in this investigation were purchased in the open market and had probably been in the dealers' warehouse 2 to 4 mo. before the first tests were made. They were similar to the cements being used daily in construction work in this district. The deterioration shown by these tests was probably greater than would be found in a larger lot of cement stored in sacks under similar conditions.

It must be recognized that many difficulties are encountered in carrying out an investigation of this kind. It is impossible to duplicate storage conditions from time to time, since much depends on the weather. Maximum variations must be expected in the results of tests made on small lots of cement and extending over a long period of time. The presence of lumps in the cement is a disturbing factor.

The further investigations now under way on bin-stored cements will form the subject-matter of a subsequent report.

TABLE 1.—SIEVE ANALYSIS OF AGGREGATE.

The sand and pebbles were screened into 8 different sizes and recombined for each concrete cylinder to conform to the sieve analysis given below.

Sieves were of square mesh, woven-wire from the "Tyler Standard Screen Scale", manufactured by The W. S. Tyler Co., Cleveland, O.

Weight of aggregate, 135 lb. per cu. ft.

Sieve No. or Size	Size of Square Opening inches	Amounts Coarser than each Sieve Percent of Weight
100	.0058	94
48	.0116	91
28	.023	87
14	.046	81
8	.093	73
4	.185	62
3/8 in.	.37	46
3/4 in.	.75	23
1 1/2 in.	1.5	0
Fineness Modulus (m)*		5.57

* The "fineness modulus" (m) of an aggregate is the sum of the percentages in the sieve analysis, divided by 100. For further details see "Design of Concrete Mixtures," Bulletin 1, Structural Materials Research Laboratory.

TABLE 2.—TIME OF SETTING OF CEMENTS.

Fineness tests of cement as received gave the following residues on 200-mesh sieve: 3705, 20.5 per cent; 3827, 17.4 per cent; 3965, 18.8 per cent.

Storage		Normal Consistency	Time of Setting				Temperature				Soundness test (over boiling water)
			Vicat Needle		Gillmore Needle		First Max.		Second Max.		
Place	Time		Initial	Final	Initial	Final	Time	Temp.	Time	Temp.	
			h. m.	h. m.	h. m.	h. m.	h. m.	°C.	h. m.	°C.	
Cement 3705; Storage Began November, 1916											
	Begin	23.0	4 25	8 05	5 10	8 45	—	—	—	—	OK
(a) Testing lab.	3 mo.	23.5	6 10	9 35	7 25	10 45	0 30	31.5	6 45	41.2	OK
(cloth sacks)	6 "	23.5	5 00	10 00	7 00	11 30	0 20	34.5	6 00	43.1	OK
	1 yr.	24.0	5 45	14 10	9 00	14 10	0 30	31.0	5 30	42.1	OK
	2 "	23.5	6 20	12 10	6 55	12 40	—	—	—	—	OK
	5 "	23.5	2 45	8 40	4 00	12 20	—	—	—	—	OK
	3 mo.	23.5	6 00	10 15	6 55	10 35	0 40	31.3	6 55	41.8	OK
(b) Basement	6 "	23.5	5.45	11 00	7.35	11 30	0 30	33.7	6 10	43.0	OK
(cloth sacks)	1 yr.	24.0	5 15	14 20	9 00	14 25	0 45	31.0	4 50	40.3	OK
	2 "	23.5	6 35	13 30	7 05	14 00	—	—	—	—	OK
	5 "	23.5	2 45	9 20	3 55	12 30	—	—	—	—	OK
	3 mo.	23.5	5 40	10 05	6 10	10 50	—	—	6 40	42.0	OK
(c) Shed in yard	6 "	23.5	5 45	11 00	8 00	11 45	0 40	33.0	6 20	41.5	OK
(cloth sacks)	1 yr.	24.5	8 00	15 00	9 45	15 00	—	—	5 30	40.4	OK
	2 "	24.0	6 55	10 40	7 20	11 40	—	—	—	—	OK
	5 "	26.5	3 55	9 05	6 30	9 15	—	—	—	—	OK
(d*)	3 mo.	23.0	8 00	9 00	6 30	9 45	—	—	—	—	OK
Cement 3827; Storage Began May, 1917											
	Begin	23.0	4 30	8 15	5 30	9 00	0 15	37.0	7 10	37.0	OK
(a) Testing Lab.	3 mo.	23.0	3 15	7 00	5 30	8 00	0 25	35.0	4 50	36.1	OK
(cloth sacks)	6 "	24.0	5 20	12 55	8 30	13 00	0 40	31.8	4 30	42.4	OK
	18 "	23.0	5 25	11 50	6 10	12 30	—	—	—	—	OK
	4½ yr.	24.0	3 20	4 05	3 35	4 35	—	—	—	—	OK
(b) Basement	3 mo.	24.0	3 40	7 00	5 30	8 15	0 25	32.4	4 40	36.8	OK
	6 "	24.6	5 05	12 20	8 45	13 10	1 00	32.0	4 20	41.4	OK
	18 "	23.0	5 35	11 50	6 20	12 35	—	—	—	—	OK
	4½ yr	25.5	3 50	4 55	5 00	5 50	—	—	—	—	OK
(c) Shed in yard	3 mo.	23.0	3 30	7 30	5 30	8 00	0 25	32.4	5.10	37.5	OK
	6 "	24.4	5 30	12 45	8 45	12 50	0 50	32.3	4 00	42.6	OK
	18 "	23.5	5 45	11 25	6 25	12 10	—	—	—	—	OK
	4½ yr.	28.0	3 40	5 20	4 30	6 55	—	—	—	—	OK
(e) Shed in yard	3 mo.	23.0	3 30	7 30	5 30	8 00	0 25	31.8	5 10	37.0	OK
("Jaite"	6 "	24.0	5 55	12 10	8 45	13 00	0 40	32.0	4 00	42.5	OK
paper sacks)	18 "	23.0	5 30	11 20	6 25	12 20	—	—	—	—	OK
	4½ yr.	28.0	4 30	7 00	6 30	7 00	—	—	—	—	OK
(f) Shed in yard	3 mo.	23.0	3 15	7 15	5 30	8 15	0 30	32.2	5 00	36.6	OK
(Bemis paper	6 "	24.6	6 10	13 00	8 45	13 00	0 40	31 9	4 00	42.0	OK
sacks)	18 "	23.5	5 20	11 40	6 35	12 10	—	—	—	—	OK
	4½ yr.	28.5	3 10	4 30	3 40	4 55	—	—	—	—	OK
Cement 3965; Storage Began November, 1917											
	Begin	23.0	3 40	7 40	5 15	8 30	0 20	30.0	5 30	30.0	OK
(c) Shed in yard	3 mo.	24.0	4 20	9 30	5 20	10 15	0 45	32.2	5 55	40.0	OK
(cloth sacks)	6 "	24.0	5 00	12 30	7 45	13 00	0 30	31.8	4 45	41.6	OK
	1 yr.	24.0	5 30	9 35	6 10	10 15	—	—	5 20	44.5	OK
	2 "	25.5	9 20	13 50	10 30	14 30	—	—	5 35	42.0	OK
	4 "	25 5	3 10	7 00	4 55	7 40	—	—	—	—	OK
(g) Shed in yard	3 mo.	24.0	4 15	9 30	5 45	10 20	0 25	34.2	5 40	40.0	OK
(Lime be-	6 "	24.0	5 15	12 30	7 45	13 00	0 20	30.7	4 50	41.2	OK
tween sacks)	1 yr.	24.0	5 25	9 35	5 05	10 15	0 50	31.5	4 55	43.9	OK
	2 "	25.0	9 05	14 30	10 45	14 40	—	—	7 40	38.0	OK
	4 "	25.0	2 55	6 50	4 25	8 50	—	—	—	—	OK
(h) Shed in yard	3 mo.	24.0	4 00	9 30	5 50	10 20	0 35	33.2	5 35	41.6	OK
(Cement be-	6 "	23.5	5 00	12 30	7 00	11 45	0 55	31.4	4 55	41.2	OK
tween sacks)	1 yr.	23.6	5 20	9 25	5 10	9 10	—	—	4 55	43.0	OK
	2 "	25.0	9 10	14 25	11 00	14 25	—	—	6 45	39.5	OK
	4 "	25.0	3 05	7 20	5 05	7 25	—	—	—	—	OK

* In cloth sacks in Laboratory, 2 mo.; in bulk in metal-lined box 1 mo.

TABLE 3.—CERTAIN CHEMICAL PROPERTIES OF CEMENT 3965.

Each value is the average of 2 tests on different samples.

Storage of Cement	CO_2 Per cent	Moisture* Per cent	Loss on Ignition Per cent
Beginning of Tests—November, 1917			
	.74	.27	1.69
Cement Stored 1 Year			
(e) Shed in yard (cloth sacks)	2.02	.61	3.87
(g) Shed in yard (hydrated lime between sacks)	1.49	.44	2.92
(h) Shed in yard (cement between sacks)	1.80	.65	3.12
Cement Stored 2 Years			
(e)	4.46	1.25	6.67
(g) Same as above	3.10	1.39	5.62
(h)	3.04	1.47	5.29
Cement Stored 4 Years**			
(e)	4.55	.80	6.56
(g) Same as above	4.33	.62	5.97
(h)	4.36	.59	5.76

* After heating for 4 hr. at a temperature of from 100 to 110°C.
** All samples removed to Laboratory after 2-yr. storage.

TABLE 4.—COMPRESSIVE STRENGTH OF CONCRETE AND MORTAR.

Cement, a mixture of 4 brands purchased in Chicago market

Cements had probably been in storage in dealers' warehouses 2 to 4 mo. before tests were begun.

Aggregate used in concrete, sand and pebbles from Elgin, Ill., graded 0–1½ in. (m = 5.57).

Concrete was mixed with 7.0 per cent and standard-sand mortar with 10.3 per cent of water, by weight of dry materials in the batch. (Water-ratios 0.86 and 0.62 for concrete and mortar, respectively.)

Concrete cylinders stored in damp sand; mortar cylinders in water.

Each value is the average of 5 tests made on different days.

Cement 3705; Storage Began Nov., 1916

Cement Stored in Cloth Sacks in	Compressive Strength—lb. per sq. in. after Storing Cement for Periods Shown											
	1:5 Concrete						1:3 Standard-Sand Mortar					
	Begin	3 mo.	6 mo.	1 yr.	2 yr.	5 yr.	Begin	3 mo.	6 mo.	1 yr.	2 yr.	5 yr.
7-Day Tests												
(a) Testing Laboratory	1500	1330	1310	900	580	650	2080	1800	1640	1200	920	660
(b) Basement	—	1260	1260	810	430	690*	—	1670	1750	960	790	630*
(c) Shed in yard	—	1200	1140	710	270	350*	—	1750	1520	800	530	380*
(d) Laboratory in sacks 2 mo.; in metal-lined box 1 mo	—	1250	—	—	—	—	—	1630	—	—	—	—
28-Day Tests												
(a)	2940	2620	2550	1860	1540	1560	3800	2690	3040	1990	1580	1790
(b) Same as above	—	2520	2520	1720	1000	1700*	—	2930	2840	2030	1590	1590*
(c)	—	2240	2300	1470	600	1030*	—	2470	2750	1600	1000	980*
(d)	—	2830	—	—	—	—	—	2880	—	—	—	—
6-Month Tests												
(a)	4450	4420	4030	3680	2460	2740	5130	3880	4480	3520	2980	2670
(b) Same as above	—	4370	3850	3150	1460	2690*	—	4340	4200	2900	2910	2840*
(c)	—	4110	3640	3040	950	—	—	4210	4170	2520	1690	1560*
(d)	—	4620	—	—	—	—	—	4590	—	—	—	—
1-Year Tests												
(a)	4930	4370	4190	3250	3150	2860	5060	4220	4540	3830	3370	2890
(b) Same as above	—	4510	3820	3190	2280	2950*	—	4540	4290	3460	3040	2980*
(c)	—	4290	3720	3120	2160	—	—	4420	4500	2430	1900	1380*
(d)	—	4940	—	—	—	—	—	4280	—	—	—	—
2-Year Tests												
(a)	4610	4900	4340	4190	4010	3450	5130	4300	4210	3550	3710	3190
(b) Same as above	—	4580	4250	4270	2320	3090*	—	3650	4100	3820	3600	2700*
(c)	—	4410	3760	3990	1650	—	—	3970	4490	2800	2880	1510*
(d)	—	5250	—	—	—	—	—	4070	—	—	—	—
5-Year Tests												
(d) Same as above	6240	6410	—	—	—	—	5430	3960	—	—	—	—

*Removed to Testing Laboratory after 2-yr. storage.

TABLE 5.—STRENGTH-RATIOS FROM TABLE 4.

The strength-ratio is the strength for each condition expressed as a percentage of the strength of cement at beginning of tests. The relation between age and strength of concrete was platted for different conditions. Smooth curves were drawn through these points. The strengths at the ages shown were then taken from the curves. These strengths when reduced to percentages of the strength of the cement at the beginning of the tests, furnish the strength-ratios. By this method minor irregularities are eliminated and the true trend of the values indicated. Typical curves of this kind are shown in Fig. 10.

Cement 3705; Storage Began Nov., 1916

Cement Stored in Cloth Sacks in	Strength-Ratios after Storing Cement for Periods Shown											
	1:5 Concrete						1:3 Standard Sand Mortar					
	Begin	3 mo.	6 mo.	1 yr.	2 yr.	5 yr.	Begin	3 mo.	6 mo.	1 yr.	2 yr.	5 yr.
7-Day Tests												
(a) Testing Laboratory....	100	89	87	60	39	43	100	86	79	58	44	32
(b) Basement.....	—	84	84	54	29	46*	—	80	76	46	38	30*
(c) Shed in yard.....	—	80	76	47	18	23*	—	73	73	38	25	18*
(d) Laboratory, in sacks 2 mo.; in metal-lined box 1mo.....	—	83	—	—	—	—	—	78	—	—	—	—
28-Day Tests												
(a)	100	89	87	69	52	53	100	71	80	59	47	43
(b) Same as above	—	94	86	63	34	56*	—	77	75	48	42	42*
(c)	—	86	78	58	24	35*	—	72	72	42	26	26*
(d)	—	96	—	—	—	—	—	76	—	—	—	—
6-Month Tests												
(a)	100	92	85	76	61	62	100	83	95	72	63	57
(b) Same as above	—	98	87	69	39	60*	—	92	89	63	59	56*
(c)	—	92	82	65	29	—	—	87	89	54	36	33*
(d)	—	101	—	—	—	—	—	86	—	—	—	—
1-Year Tests												
(a)	100	93	85	75	62	61	100	85	92	74	68	58
(b) Same as above	—	92	84	68	41	60*	—	92	89	69	64	60*
(c)	—	87	75	66	30	—	—	89	91	56	38	34*
(d)	—	101	—	—	—	—	—	85	—	—	—	—
2-Year Tests												
(a)	100	92	79	72	60	61	100	83	89	74	72	60
(b) Same as above	—	83	77	64	42	56*	—	89	87	74	70	62*
(c)	—	80	68	62	32	—	—	87	89	54	48	31*
(d)	—	100	—	—	—	—	—	83	—	—	—	—
5-Year Tests												
(d) Same as above	100	98	—	—	—	—	100	79	—	—	—	—

*Cement removed to Testing Laboratory after 2-yr. storage.

TABLE 6.—COMPRESSIVE STRENGTH OF CONCRETE AND MORTAR.

Cement 3827; Storage Began May, 1917

See notes preceding Table 4.

Cement Stored in Cloth Sacks in	Compressive Strength—lb. per sq. in. after Storing Cement for Periods Shown									
	1:5 Concrete					1:3 Standard Sand Mortar				
	Begin	3 mo.	6 mo.	1½ yr.	4½ yr.	Begin	3 mo.	6 mo.	1½ yr.	4½ yr.
7-Day Tests										
(a) Testing Laboratory	1640	1220	1000	770	—	2090	1540	1520	960	650
(b) Basement	—	1050	990	610	760*	—	1190	1440	840	690*
(c) Shed in yard	—	1090	940	690	330*	—	1360	1320	940	310*
(e) Shed in yard, "Jaite" paper sacks	—	1140	970	720	340*	—	1530	1310	1090	390*
(f) Shed in yard, "Bemis" paper sacks	—	1200	900	720	330*	—	1360	1520	1010	430*
28-Day Tests										
(a)	3560	2500	1920	1730	—	3620	2680	2290	1590	1670
(b)	—	2070	1880	1450	1740*	—	2570	2220	1670	1620*
(c) Same as above	—	2080	1890	1380	1150*	—	2630	2190	1740	860*
(e)	—	2280	1930	1490	930*	—	2710	2540	1830	930*
(f)	—	2300	1840	1490	820*	—	2530	2320	1610	970*
6-Month Tests										
(a)	5040	3710	3850	3050	—	5810	4170	4210	3050	2880
(b)	—	2970	3850	2430	2690*	—	3510	4280	2790	2690*
(c) Same as above	—	3240	3690	2460	1900*	—	4050	4070	2670	1410*
(e)	—	3490	3500	2760	1580*	—	3920	4340	2610	1860*
(f)	—	3320	3520	2130	1490*	—	3880	3980	2710	1940*
1-Year Tests										
(a)	5390	3530	3920	3630	—	5370	4160	4030	3480	2000
(b)	—	3920	3610	3120	—	—	3820	3480	2970	2590*
(c) Same as above	—	3920	3220	3000	1830*	—	4140	3730	3340	1320*
(e)	—	4100	3460	3110	1750*	—	4230	3480	3190	1840*
(f)	—	3710	2940	3440	—	—	3800	3980	3500	1890*
2-Year Tests										
(a)	5150	4640	4860	4340	—	5020	4040	4500	3460	3590
(b)	—	4220	4170	3360	—	—	3940	4410	3110	2870*
(c) Same as above	—	3950	4120	3270	—	—	3730	4400	3260	1710*
(e)	—	4570	4470	3540	—	—	4100	4330	3640	1700*
(f)	—	4580	4170	3380	—	—	4190	4720	3460	2100*
5-Year Tests										
	6400	—	—	—	—	4700	—	—	—	—

* Cement removed to Testing Laboratory after 2 yr. storage.

TABLE 7.—STRENGTH-RATIOS FROM TABLE 6.

Cement 3827; Storage Began May, 1917

See notes preceding Table 5.

Cement Stored in Cloth Sacks in	Strength-Ratios after Storing Cement for Periods Shown									
	1:5 Concrete					1:3 Standard-Sand Mortar				
	Begin	3 mo.	6 mo.	1 yr.	4½ yr.	Begin	3 mo.	6 mo.	1 yr.	4½ yr.
7-Day Tests										
(a) Testing Laboratory	100	74	61	47	..	100	74	73	35	31
(b) Basement	—	64	54	37	46*	—	70	69	40	33*
(c) Shed in yard, cloth sacks	—	66	57	42	28*	—	65	63	45	15*
(e) Shed in yard, "Jaite" paper sacks	—	70	59	44	21*	—	73	63	52	19*
(f) Shed in yard, "Bemis" paper sacks	—	73	55	44	20*	—	65	73	48	21*
28-Day Tests										
(a)	100	70	61	49	—	100	74	71	48	46
(b)	—	58	53	41	46*	—	68	61	49	45*
(c) Same as above	—	56	53	41	29*	—	75	68	48	24*
(e)	—	62	57	44	26*	—	75	70	51	28*
(f)	—	61	52	42	23*	—	70	68	47	27*
6-Month Tests										
(a)	100	76	72	61	—	100	74	68	55	52
(b)	—	60	63	50	56*	—	63	57	50	46*
(c) Same as above	—	62	62	49	36*	—	70	68	49	25*
(e)	—	71	68	53	31*	—	72	69	50	30*
(f)	—	68	63	51	30*	—	66	67	49	29*
1-Year Tests										
(a)	100	78	74	66	—	100	78	77	65	60
(b)	—	52	66	54	—	—	71	65	55	51*
(c) Same as above	—	66	66	53	38*	—	77	77	57	28*
(e)	—	75	72	57	32*	—	79	76	59	34*
(f)	—	72	67	54	—	—	74	79	57	35*
2-Year Tests										
(a)	100	82	77	73	—	100	80	88	75	71
(b)	—	76	74	60	—	—	78	73	62	57*
(c) Same as above	—	72	73	58	—	—	84	88	65	33*
(e)	—	81	79	63	—	—	88	86	71	39*
(f)	—	78	74	60	—	—	84	94	69	42*

* Removed to Testing Laboratory after 2-yr. storage.

TABLE 8.—COMPRESSIVE STRENGTH OF CONCRETE AND MORTAR.

Cement 3965; Storage Began Nov., 1917

See notes preceding Table 4.

Cement Stored in Cloth Sacks in	Compressive Strength—lb. per sq. in. after Storing Cement for Periods Shown											
	1:5 Concrete						1:3 Standard-Sand Mortar					
	Begin	3 mo.	6 mo.	1 yr.	2 yr.	4 yr.*	Begin	3 mo.	6 mo.	1 yr.	2 yr.	4 yr.*
7-Day Tests												
(c) Shed in yard.....	1280	800	730	570	470	530	1770	1350	1150	1200	600	430
(g) Shed in yard, hydrated lime between sacks...	—	1060	880	650	520	610	—	1530	1150	1010	660	540
(h) Shed in yard, cement between sacks.....	—	980	940	600	580	590	—	1360	1160	910	670	650
28-Day Tests												
(c)	2560	1760	1750	1080	1100	1320	3360	2140	2060	2110	1170	1170
(g) Same as above	—	1880	1810	1590	1180	1450	—	2440	1880	1840	1580	1500
(h)	—	1730	1930	1370	1230	1450	—	2260	2210	1730	1580	1440
6-Month Tests												
(c)	3760	3480	2600	2230	2500	2160	4980	3800	3670	3200	2420	1790
(g) Same as above	—	3340	2760	2810	2630	2480	—	3890	2920	2760	2740	2320
(h)	—	3570	2930	2290	2550	2130	—	3920	3160	2850	3200	2600
1-Year Tests												
(c)	3720	3930	2890	2710	2840	2460	4490	3040	3550	3480	2280	1830
(g) Same as above	—	4190	3740	3160	2860	2610	—	3700	3800	3400	2950	2240
(h)	—	3780	3300	3020	2880	2580	—	3570	3810	3520	3180	2710
2-Year Tests												
(c)	4970	4430	4310	2520	3190	2700	4650	4050	3950	3590	2710	1730
(g) Same as above	—	4920	4180	3550	3370	3160	—	4450	3890	3580	3290	2580
(h)	—	4620	4290	2920	3330	—	—	3580	3570	3100	3000	2740
5-Year Tests												
	5450	—	—	—	—	—	3440	—	—	—	—	—

*Removed to Testing Laboratory after 2-yr. storage; Cement tested at 2 and 4-yr. storage periods contained about 50 per cent pulverized lumps.

TABLE 9.—STRENGTH-RATIOS FROM TABLE 8.

Cement 3965; Storage Began Nov., 1917

See notes preceding Table 5.

Cement Stored in.. ..... Cloth Sacks in	Strength-Ratios after Storing Cement for Periods Shown											
	1:5 Concrete						1:3 Standard-Sand Mortar					
	Begin	3 mo.	6 mo.	1 yr.	2 yr.	4 yr.*	Begin	3 mo.	6 mo.	1 yr.	2 yr.	4 yr.*
7-Day Tests												
(c) Shed in yard.....	100	63	57	45	37	41	100	76	65	63	30	24
(g) Shed in yard, hydrated lime between sacks...	—	69	65	51	41	48	—	86	65	57	37	31
(h) Shed in yard, cement between sacks.....	—	79	74	47	45	46	—	77	66	51	38	37
28-Day Tests												
(c) Same as above	100	78	70	52	57	53	100	64	61	60	39	35
(g)	—	81	73	64	55	58	—	73	56	55	47	40
(h)	—	76	78	55	56	55	—	67	62	52	55	45
6-Month Tests												
(c) Same as above	100	93	79	59	66	59	100	68	67	68	47	36
(g)	—	95	85	75	66	66	—	77	64	60	58	46
(h)	—	90	78	63	68	61	—	71	68	59	64	53
1-Year Tests												
(c) Same as above	100	92	78	57	66	57	100	75	74	72	51	38
(g)	—	98	87	74	67	65	—	81	71	67	61	50
(h)	—	92	77	62	67	60	—	74	74	63	66	56
2-Year Tests												
(c) Same as above	100	93	77	54	67	57	100	87	84	77	58	41
(g)	—	100	88	74	71	66	—	88	83	76	70	55
(h)	—	94	74	61	70	—	—	76	83	69	73	62

*Removed to Testing Laboratory after 2-yr. storage; Cement tested at 2 and 4-yr. storage periods contained about 50 per cent pulverized lumps.

TABLE 10.—SUMMARY OF STRENGTH TESTS OF 1:5 CONCRETE.

Values are the average of 2 samples for storage conditions (a) and (b) and 3 samples for (c) from Tables 4 to 9, unless otherwise noted.

The (c) values include all types of shed-in-yard storage; the strengths at the beginning of the tests are different than for (a) and (b) due to the difference in number of samples of cement included in the averages.

All cements were stored in Laboratory after 2-yr.

Cement Stored in Cloth Sacks in	Strength of 1:5 Concrete after Storing Cement for Periods Shown											
	Compressive Strength—lb. per sq. in.						Strength-Ratios					
	Begin	3 mo.	6 mo.	1 yr.	2 yr.	4½ yr.	Begin	3 mo.	6 mo.	1 yr.	2 yr.	4½ yr.
7-Day Tests												
(a) Testing Laboratory...	1570	1280	1160	900*	680	650*	100	82	74	60*	43	43*
(b) Basement.....	1570	1160	1120	810*	520	720	100	74	69	54*	33	46
(c) Shed-in-yard.....	1470	1100	980	660	500	420	100	73	66	48	34	30
28-Day Tests												
(a)	3250	2560	2240	1860*	1640	1560*	100	80	74	69*	50	53*
(b) Same as above	3250	2300	2200	1720*	1220	1720	100	76	70	63*	38	51
(c)	3020	2080	2010	1410	1070	1140	100	75	69	58	41	39
6-Month Tests												
(a)	4740	4060	3940	3680*	2760	2740*	100	84	78	76*	61	62*
(b) Same as above	4740	3670	3850	3150*	1940	2690	100	79	75	69*	44	58
(c)	4410	3970	3320	2740	1990	1960	100	84	76	66	49	47
1-Year Tests												
(a)	5160	3950	4060	3250*	3390	2860*	100	86	80	75*	64	61*
(b) Same as above	5160	4220	3720	3190*	2700	2950*	100	72	75	68*	46	60*
(c)	4680	4050	3410	3040	2730	2370	100	84	75	65	51	48
2-Year Tests												
(a)	4880	4770	4600	4190*	4180	3450*	100	87	78	72*	64	61*
(b) Same as above	4880	4400	4210	4270*	2840	3090*	100	80	76	64*	51	56*
(c)	4810	4480	4090	3490	2890	2930	100	84	75	62	54	62
5-Year Tests												
(a)	6320	—	—	—	—	—	—	—	—	—	—	—
(b) Same as above	6320	—	—	—	—	—	—	—	—	—	—	—
(c)	6030	—	—	—	—	—	—	—	—	—	—	—

*Based on 1 sample from Tables 4 and 5.

TABLE 11.—EFFECT OF CONDITION OF STORAGE OF CEMENT.

Average of all test ages from Table 10.

Cement Stored in Cloth Sacks in	Strength-Ratios after Storing Cement for Periods Shown												Grand Average
	1:5 Concrete						1:3 Standard-Sand Mortar						
	Begin	3 mo.	6 mo.	1 yr.	2 yr.	4½yr	Begin	3 mo.	6 mo.	1 yr.	2 yr.	4½yr	
(a) Testing Laboratory	100	84	77	70	57	57	100	79	81	67	57	52	68
(b) Basement	—	76	73	64	43	54*	—	78	74	60	53	48*	62
(c) Shed in yard	—	80	72	60	46	45*	—	77	75	56	47	33*	59
Average		80	74	65	49	52		78	77	61	52	44	63

* Removed to Testing Laboratory after 2-yr. storage.

TABLE 12.—CLOTH VS. PAPER CEMENT SACKS.

Average of all test ages in Table 7 for cement stored in shed-in-yard; cements removed to Testing Laboratory after 2-yr.

Cement Stored in	Strength-Ratios after Storing Cement for Periods Shown										Grand Average
	1:5 Concrete					1:3 Standard-Sand Mortar					
	Begin	3 mo.	6 mo.	1½ yr.	4½ yr.	Begin	3 mo.	6 mo.	1½ yr.	4½ yr.	
(c) Cloth sacks	100	64	62	49	33	100	74	73	53	25	54
(e) "Jaite" paper sacks	—	72	67	52	28	—	77	73	57	30	57
(f) "Bemis" paper sacks	—	70	62	50	24	—	72	76	54	31	55
Average		69	64	50	28		74	74	55	29	55

TABLE 13.—EFFECT OF HYDRATED LIME AND PORTLAND CEMENT AS COVERINGS FOR CEMENT SACKS.

Average of all test ages in Table 9. Cement stored in shed-in-yard up to 2 yr.; thereafter in Testing Laboratory.

Storage Condition of Cement	Strength-Ratios after Storing Cement for Periods Shown												Grand Average
	1:5 Concrete						1:3 Standard-Sand Mortar						
	Begin	3 mo.	6 mo.	1 yr.	2 yr.	4 yr.	Begin	3 mo.	6 mo.	1 yr.	2 yr.	4 yr.	
(c) Sacks uncovered	100	84	72	53	59	53	100	74	70	68	45	35	61
(g) Sacks surrounded by hydrated lime	—	89	80	68	60	61	—	81	68	63	55	45	67
(h) Sacks surrounded by portland cement	—	86	76	58	61	56	—	73	71	59	59	51	65
Average		86	76	60	60	57		76	70	63	53	44	64

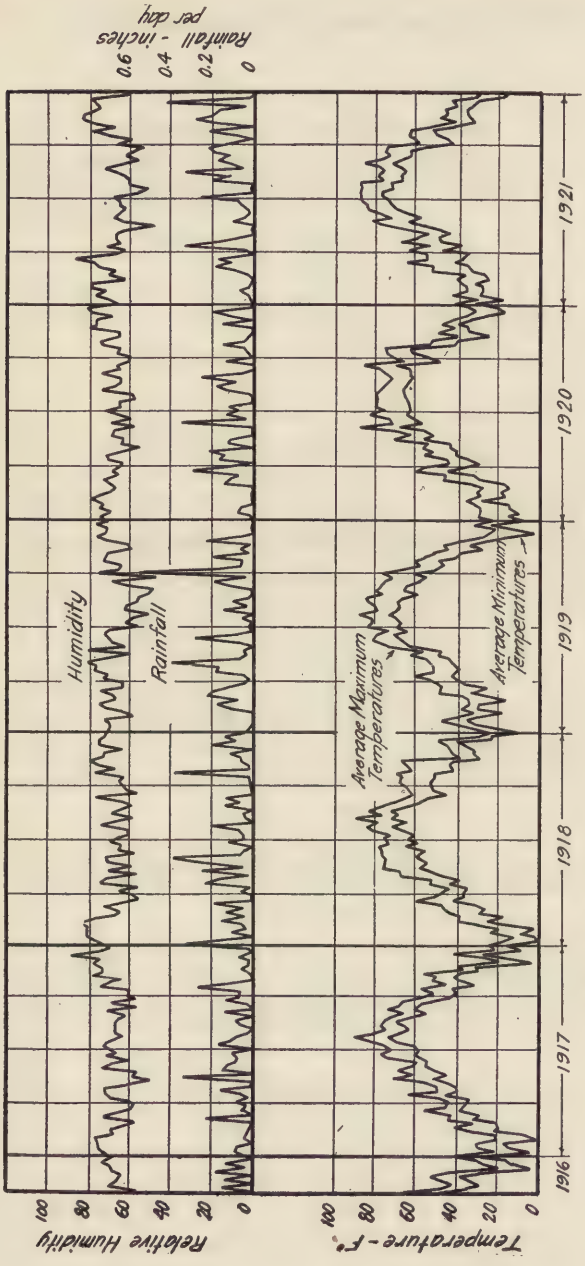


FIG. 1. TEMPERATURE, RAINFALL AND HUMIDITY DURING STORAGE OF CEMENT.

Curves show weekly averages from the Chicago Monthly Meteorological Summary of the U. S. Department of Agriculture.

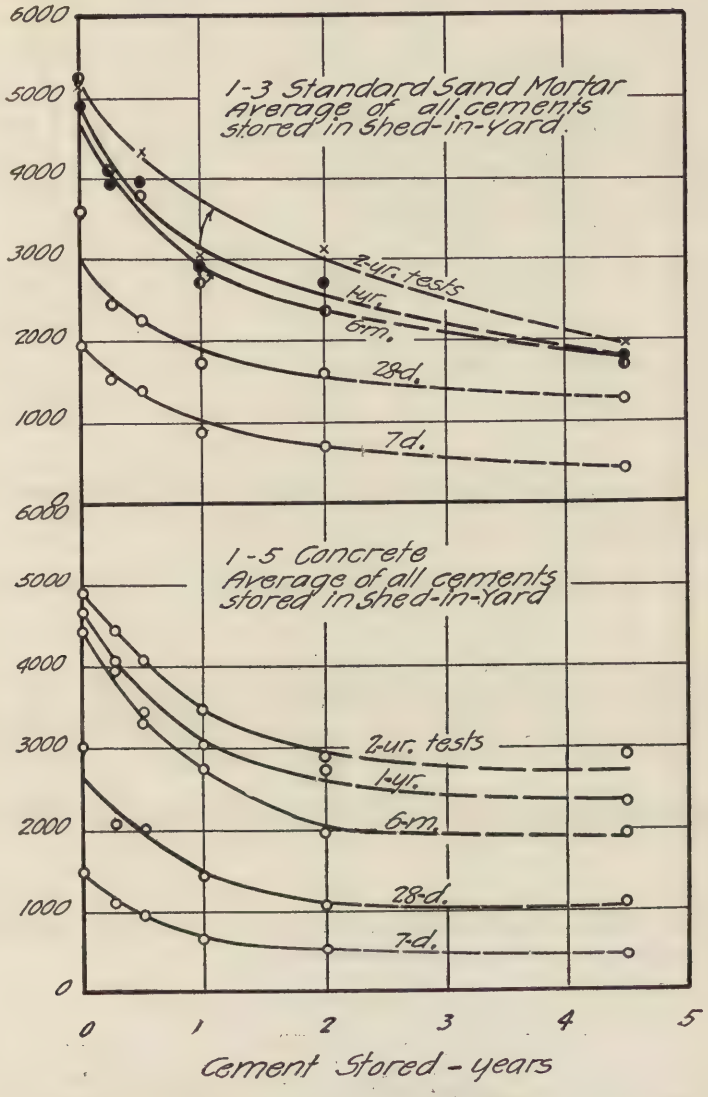


FIG. 2. SUMMARY OF TESTS OF CEMENTS STORED IN SHED UP TO 4½ YR.

Values for concrete from Table 10; mortar average of values from Tables 4, 6 and 8;
In Fig. 3 the same data are expressed as strength-ratios.
It should be noted that shed storage was the most severe of the conditions covered by these tests.

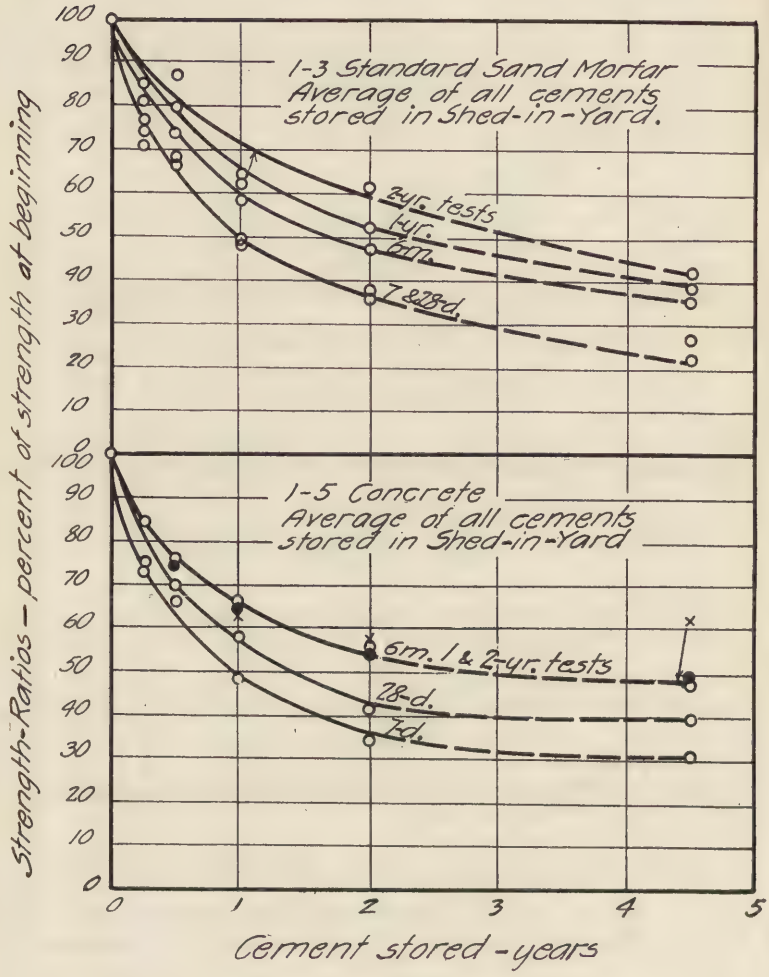


FIG. 3. STRENGTH RATIOS FOR CONCRETE AND MORTAR TESTS IN FIG. 2.

Values for concrete from Table 10; mortar, average of values from Tables 5, 7 and 9.

It should be noted that shed storage was the most severe of the conditions covered by these tests.

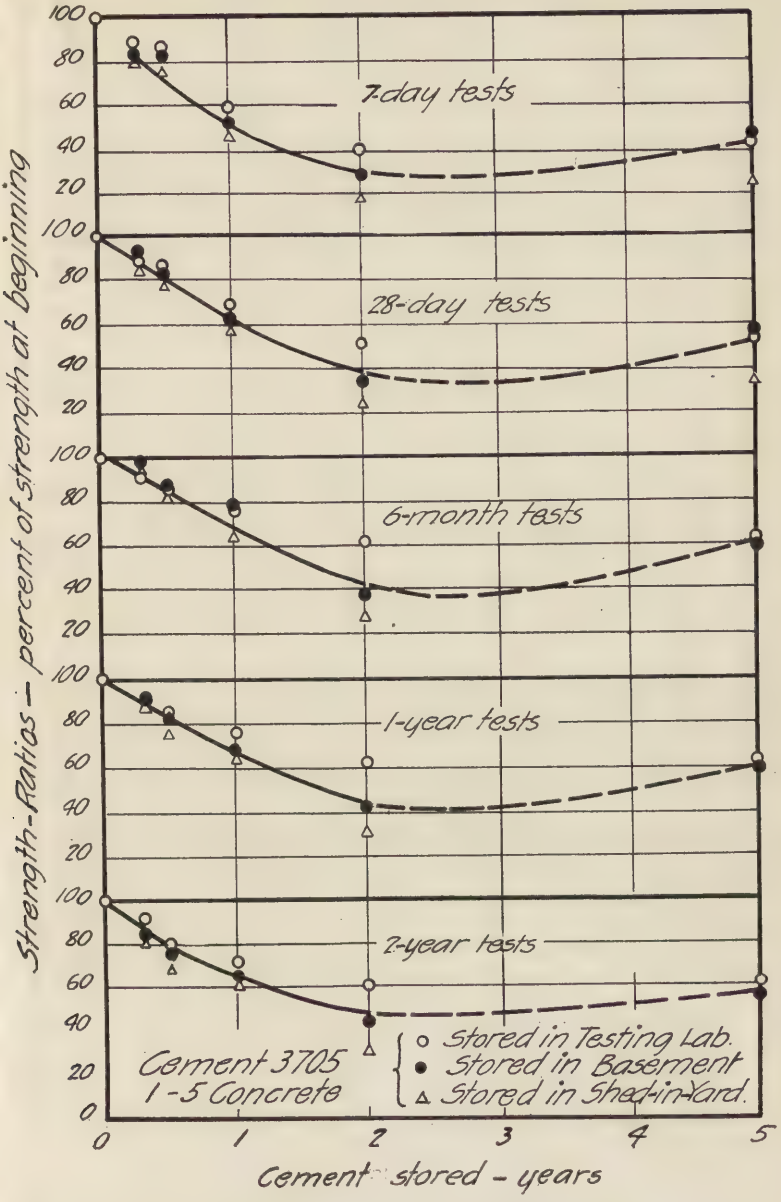


FIG. 4. STRENGTH RATIOS FOR 1:5 CONCRETE; CEMENT 3705.

Data from Table 5. Compare Fig. 6 and 8.
Curves are average for the 3 conditions of storage.
All cements stored in Laboratory after 2 yr.

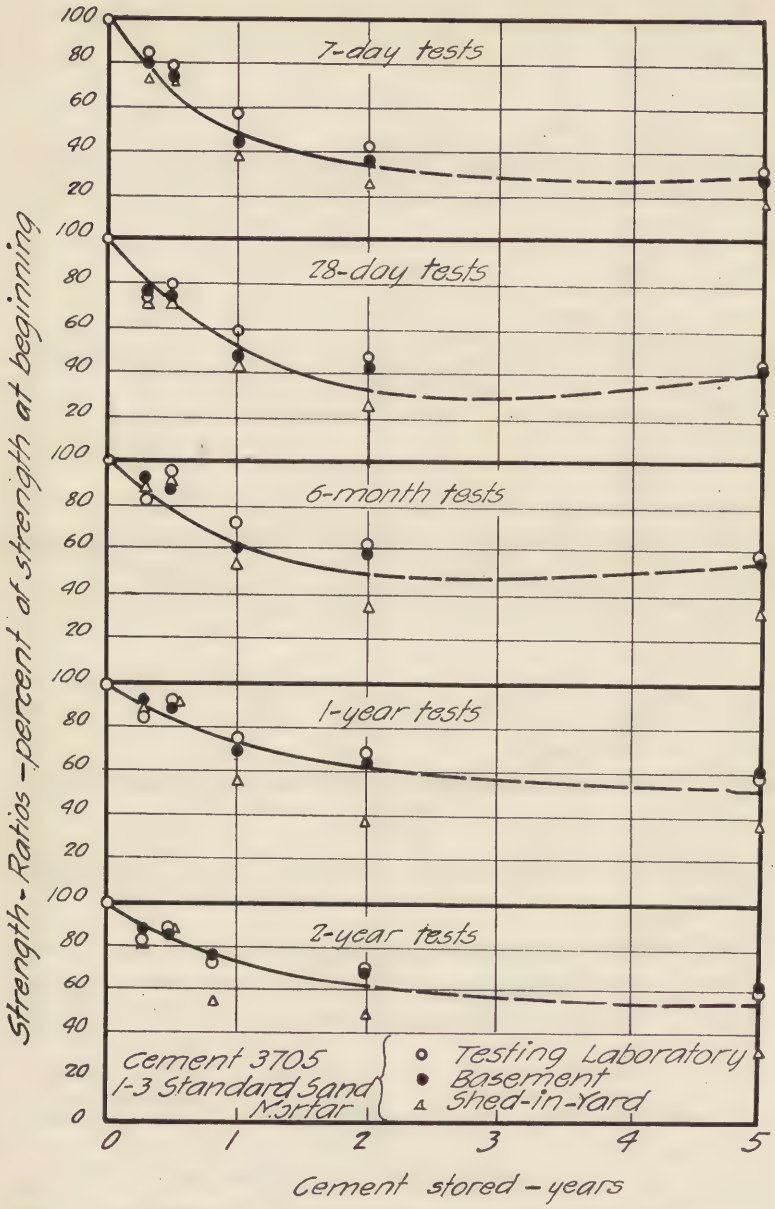


FIG. 5. STRENGTH RATIOS FOR 1:3 STANDARD-SAND MORTAR; CEMENT 3705.

Data from Table 5. Compare Fig. 7 and 9.
Curves are average for the 3 conditions of storage.
All cements stored in Laboratory after 2 yr.

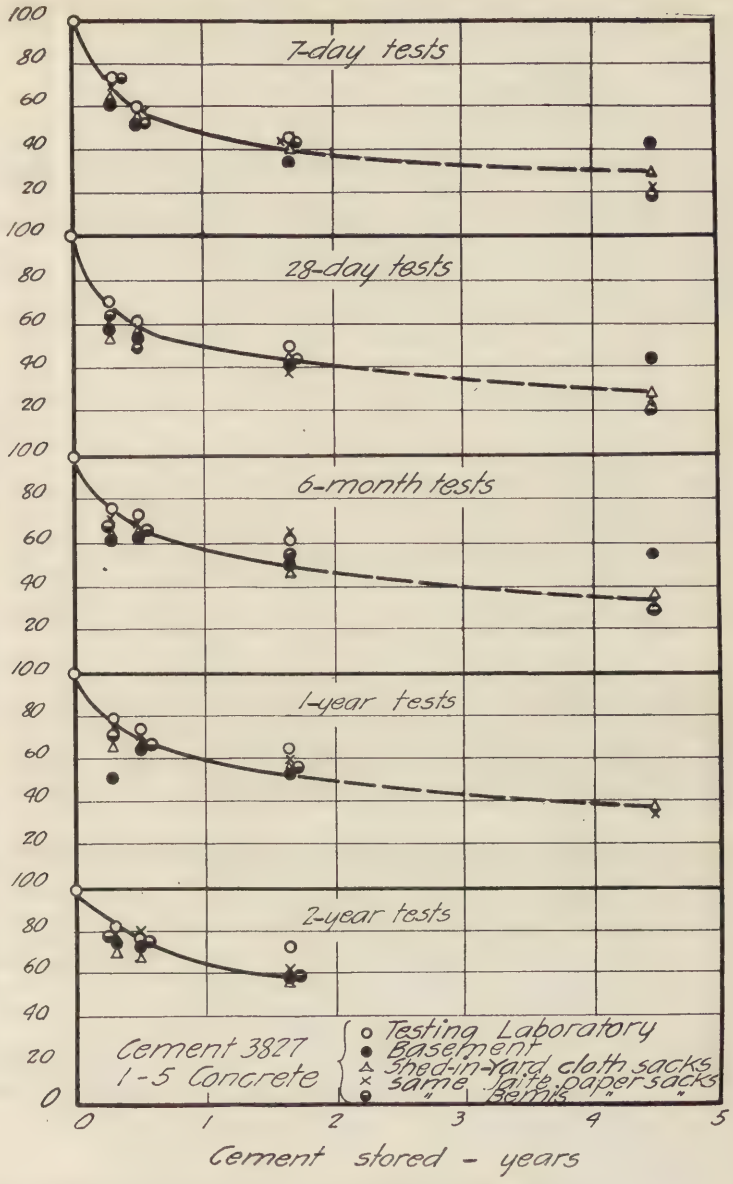


FIG. 6. STRENGTH RATIOS FOR 1:5 CONCRETE; CEMENT 3827.

Data from Table 7. Compare Fig. 4 and 8.
Curves are average for the 5 conditions of storage.
All cements stored in Laboratory after 2 yr.

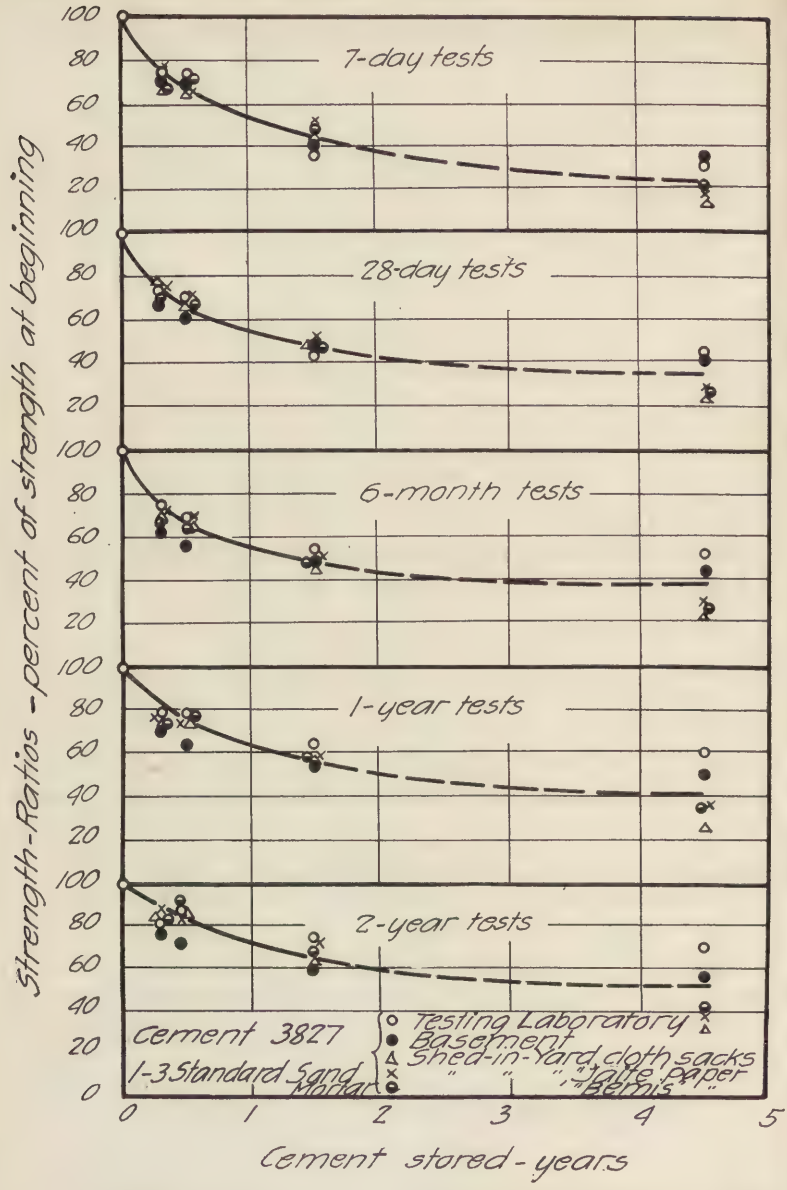


FIG. 7. STRENGTH RATIOS FOR 1:3 STANDARD-SAND MORTAR; CEMENT 3827.

Data from Table 7. Compare Fig. 5 and 9.
Curves are average for the 5 conditions of storage.
All cements stored in Laboratory after 2 yr.

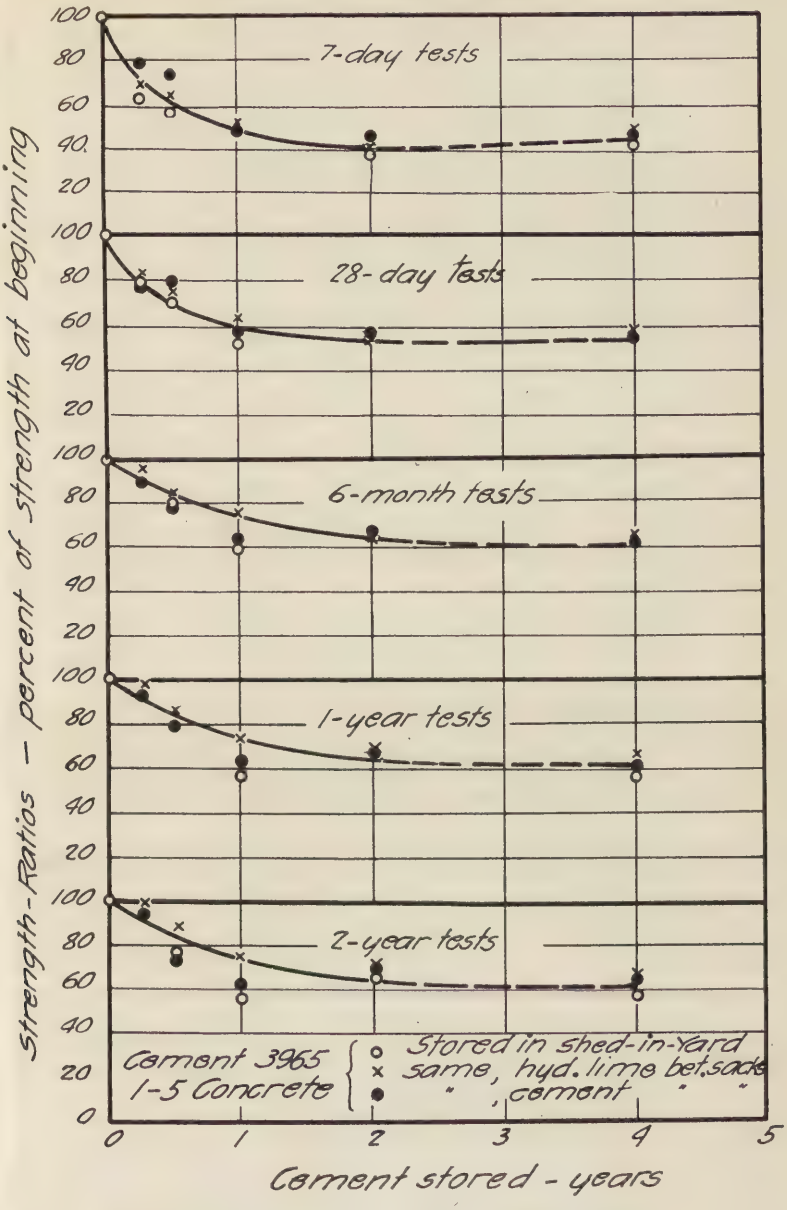


FIG. 8. STRENGTH RATIOS FOR 1:5 CONCRETE; CEMENT 3965.

Data from Table 9. Compare Fig. 4 and 6.
Curves are average for the 3 conditions of storage.
All cements stored in Laboratory after 2 yr.

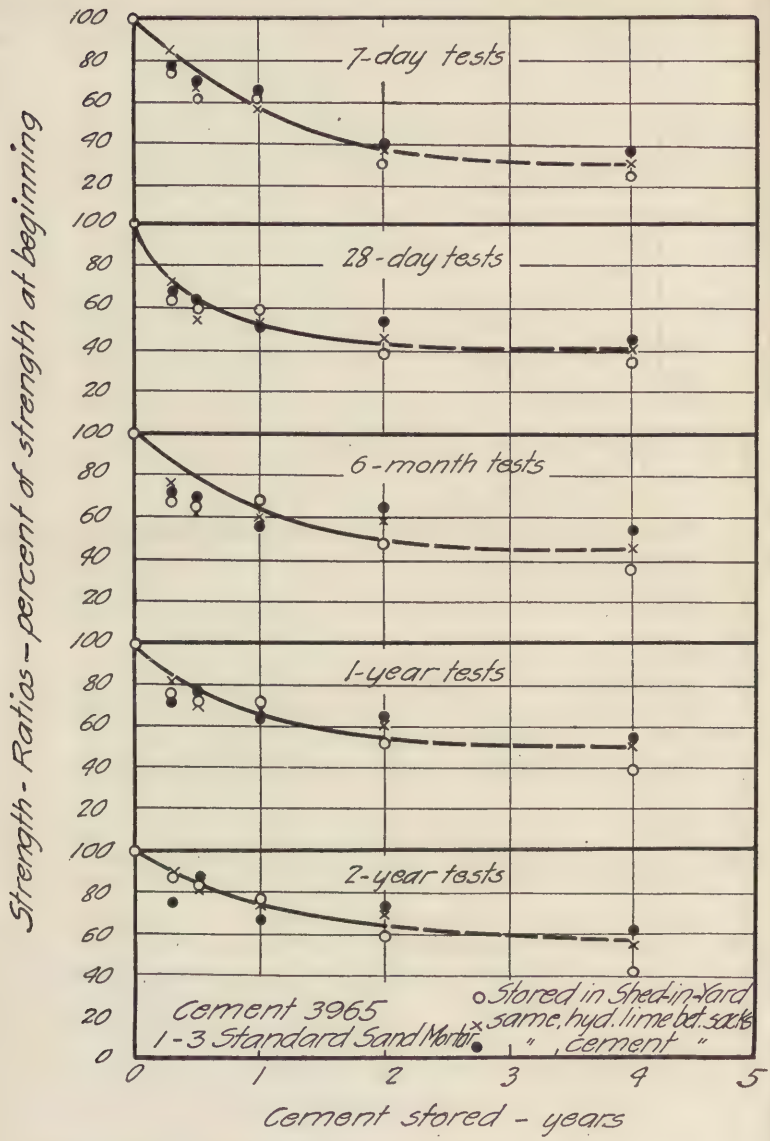


FIG. 9. STRENGTH RATIOS FOR 1:3 STANDARD-SAND MORTAR; CEMENT 3965.

Data from Table 9. Compare Fig. 5 and 7.
Curves are average for the 3 conditions of storage.
All cements stored in Laboratory after 2 yr.

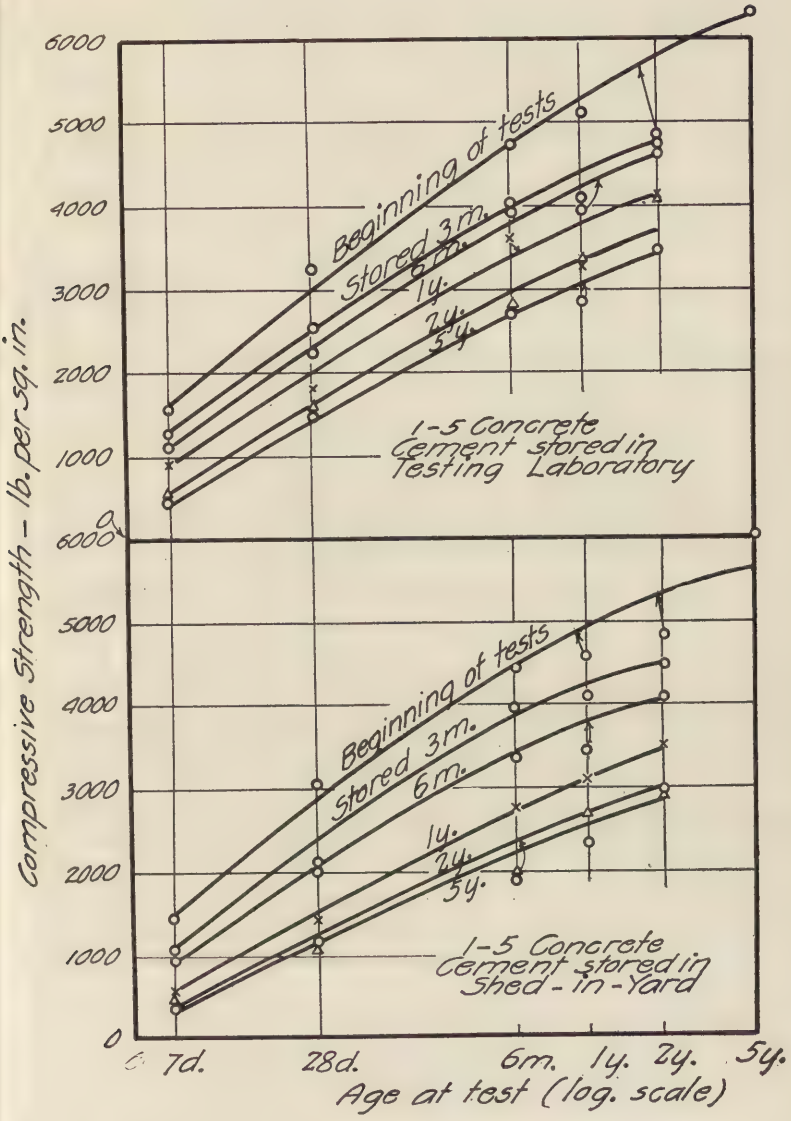


FIG. 10. EFFECT OF AGE ON THE STRENGTH OF CONCRETE.

Data from Table 10.
Strength-ratios in Tables 5, 7 and 9, and Fig. 3 to 9 were calculated from curves of this type.

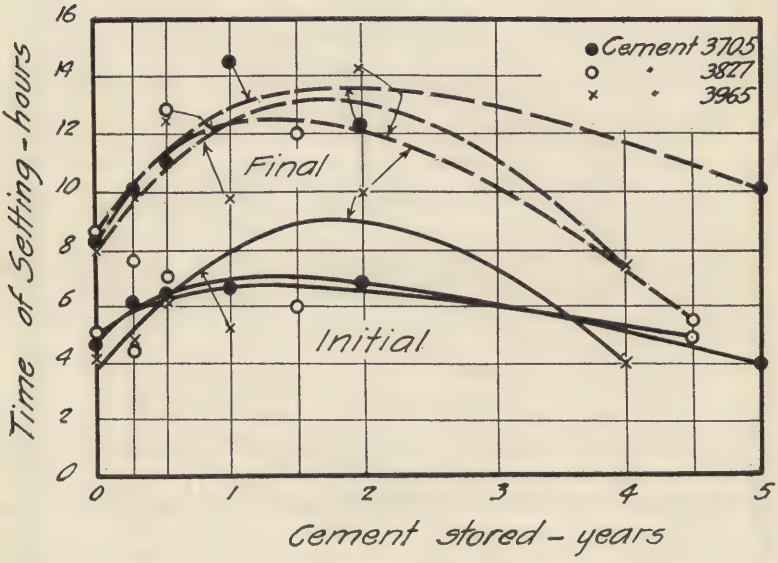


FIG. 11. EFFECT OF STORAGE OF CEMENT ON THE TIME OF SETTING.

Data from Table 2.
Curves are average for all conditions of storage.

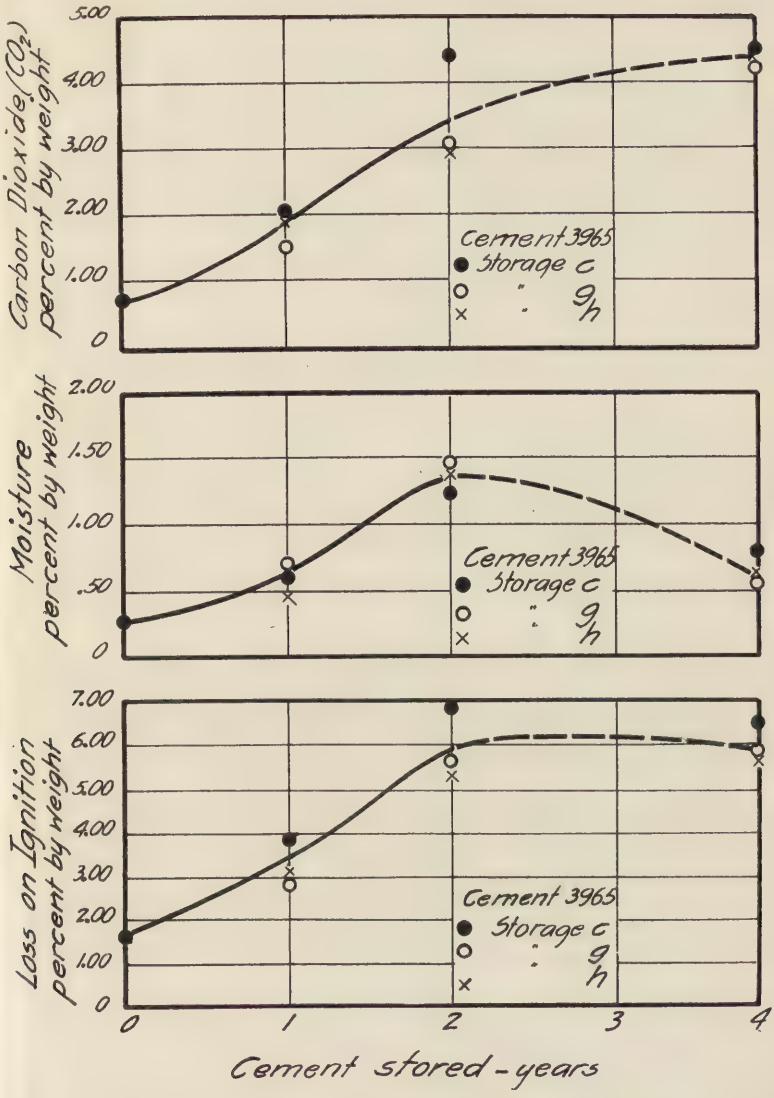


FIG. 12. EFFECT OF STORAGE OF CEMENT ON CERTAIN CHEMICAL PROPERTIES.

Data from Table 3.

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Bulletin 7

Structural Materials Research Laboratory
Lewis Institute
Chicago

Effect of Tannic Acid on the Strength of Concrete

By

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Professor in Charge of Laboratory

(Authorized Reprint from the Copyrighted Proceedings of the American Society for Testing Materials, Vol. XX, Part I, 1920)

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FOREWORD

This paper was originally published in the copyrighted Proceedings of the American Society for Testing Materials, Vol. XX, Part I, 1920, as an Appendix to the Annual Report of Committee C-9 on Concrete and Concrete Aggregates. Acknowledgment is made to the Society for permission to reprint the paper in bulletin form.

In the second and third printings, no changes were made in the text, tables, or figures. The bibliography has been revised to include a few references which did not appear in the original report.

EFFECT OF TANNIC ACID ON THE STRENGTH OF CONCRETE.

By Duff A. Abrams.

SUMMARY.

It has long been recognized that impurities of an organic nature have the effect of reducing the strength of concrete or entirely destroying the hydraulic properties of the cement. While this fact has been pointed out by a number of writers, there is still a tendency among concrete engineers to disregard the effect of such impurities. A general investigation of this subject was inaugurated in 1915 by means of funds furnished by Committee C-9 on Concrete and Concrete Aggregates and has been continued during the past four years as a part of the investigations being carried out through the cooperation of Lewis Institute and the Portland Cement Association.

It was impossible to secure natural sands containing graduated percentages of organic impurities for a study of the *quantitative* effect of such impurities. Consequently, aggregate samples were prepared in which known quantities of organic impurities were present, by applying tannic acid as a surface coating in quantities up to 0.40 per cent by weight. Compression tests were made on 3 by 6-in. concrete cylinders. The mix varied from 1:5 to 1:2; the size of aggregate ranged from a fine sand to a ¾-in. graded aggregate. Tests were made on all mixtures and sizes of aggregate at ages of 7 days, 28 days, 3 months, 1 year, and 2 years. Specimens were stored in damp sand. This series included about 2000 concrete tests.

Following are the principal conclusions from this investigation:

1. It is believed that the results of these tests are, in general, typical of the effect produced by organic impurities in concrete, judging from tests with natural sands containing organic matter, made in Lewis Institute and other laboratories.

2. The strength of concrete was reduced for all percentages of tannic acid, for all mixes and ages covered by these tests. Less than 0.1 per cent of tannic acid in terms of the weight of the aggregate may reduce the strength of the concrete to one-half its normal value.

3. Lean mixtures are more affected by tannic acid than rich ones.

4. The mixtures from the finer aggregates are less affected by tannic acid than those from the coarser aggregates.

5. All of the effects mentioned above may be summed up by saying that the reduction in strength of concrete is a function of the *concentration* of tannic acid in the mixing water. An equation is given which represents this relation for the 28-day tests.

6. The results of these tests indicate that the wetter consistencies would be less affected by the presence of organic impurities than the drier ones.

7. The strength falls off rapidly for small percentages of tannic acid and less rapidly as higher percentages are reached.

8. The 7 and 28-day strengths are reduced to a greater extent by tannic acid than those at ages of 1 and 2 years.

9. Some of the 1:5 mixes in which the higher percentages of tannic acid and the finer sands were used (2 to 3-per-cent solution) disintegrated before the time of test. The 1:7 mixes (3 to 5-per-cent solution) were destroyed in removing the molds.

10. The tests confirm the results of many other investigations made in this Laboratory in showing the fundamental dependency of strength of concrete on the quantity of mixing water as expressed by the water-ratio.

11. The strength of concrete (stored in a damp place) both with and without tannic acid increased with age. The strength for a given condition was a logarithmic function of the age.

Care should be taken to eliminate surface loam from concrete sands. Loam can generally be removed by washing.

Attention is called to the "colorimetric" test with sodium hydroxide as a convenient method of testing for organic impurities in natural sands.

EFFECT OF TANNIC ACID ON THE STRENGTH OF CONCRETE.

By Duff A. Abrams.

Introduction.

It has long been recognized that organic impurities are injurious in sands used for both cement and lime mortars. Contamination from surface loam and the presence of other organic materials peculiar to local conditions are the principal sources of organic impurities in sands. Many specifications for concrete aggregate require that the sand be clean, but definite information has been lacking as to the exact effect of organic impurities on concretes of widely different composition.

The necessity for clean sand was fully appreciated by the ancients as shown by the following extract from "A Treatise on Architecture," by Vitruvius, a Roman architect and engineer; written about 100 B. C.

"In buildings of rubble work it is of the first importance that the sand be fit for mixing with the lime and unalloyed with earth." Book 1, Chapter 4.)

Many modern writers have pointed out the injurious effect of organic materials in concrete. However, in spite of the numerous warnings, there is a tendency to disregard the dangers which lie in the use of sands containing organic impurities which may come from contamination of surface loam and other foreign material.

The U. S. Department of Agriculture reports (Bulletin 47, Bureau of Soils) that the ordinary top soil contains on the average over 2 per cent of organic matter. This value is based on many thousand tests on samples from all sections of the country. In many instances the organic material is much higher than 2 per cent. The sub-soil for several feet in depth contains an appreciable percentage of organic material.

A general investigation of the whole subject of the effect of organic impurities on mortars and concretes was begun at Lewis Institute, in 1915, by means of funds appropriated by Committee C-9 on Concrete and Concrete Aggregates. The earlier investigations covered the study of the concrete-making properties of natural sands containing organic impurities of such a nature as to be injurious to concrete. A preliminary report under the title of "Colorimetric Tests for Organic Impurities in Sands"[1] was published in 1917. That report indicated a method of testing for organic impurities which consists of digesting a sample of the sand in a dilute solution of sodium hydroxide and observing the color of the resulting liquid.

Later investigations of the effect of organic impurities have been conducted as a part of the experimental studies of concrete and concrete

[1]Appendix II, Report of Committee C-9, *Proceedings*, Am. Soc. Testing Mat., Vol. XVII, Part I, p. 327 (1917).

See also "Abrams-Harder Field Test for Organic Impurities in Sands," Report of Committee C-9, *Proceedings*, Am. Soc. Testing Mat., Vol. XIX, Part I, p. 321 (1919).

materials being carried out through the cooperation of Lewis Institute and the Portland Cement Association at the Structural Materials Research Laboratory. The tests covered by this report were made under the immediate supervision of Dr. Oscar E. Harder, former Research Chemist in this Laboratory.

In this investigation it was necessary to use an artificially prepared sand, due to the fact that no natural sands could be found which contained graduated percentages of organic impurities in sufficient quantities to enable us to investigate the *quantitative* effect of such material in concrete of different mixtures made up of aggregate of different size, tested at different ages, etc. The characteristic compounds which are commonly found to be injurious in natural sands are of a humus nature—frequently tannates of some form. This condition suggested the use of tannic acid as a means of conducting further studies of the effect of organic impurities on the strength and other properties of concrete. It is believed that the results secured from this study may be considered typical of the effect of organic impurities in natural sands.

OUTLINE OF TESTS.

This investigation comprised compression tests of 2000 3 by 6-in. cylinders made of concrete[1] from sand and pebbles of different sizes, ranging from 0 – No. 28-sieve sand to 0 – ¾-in. aggregate. In each instance the tannic acid content was varied up to 0.40 per cent of the weight of the aggregate.

The following variables were covered by the tests:

SIZE OF AGGREGATE.	MIX BY VOLUME.	TANNIC ACID, PER CENT BY WEIGHT OF AGGREGATE.	AGE AT TEST.
0 to No. 28	1:5	0.0	7 days
0 to No. 14	1:4	0.05	28 days
0 to No. 8	1:3	0.10	3 months
0 to No. 4	1:2	0.20	1 year
0 to ⅜ in.		0.40	2 years
0 to ¾ in.			

All possible combinations of the above factors were used in this investigation. Each strength value is based on four tests made on different days at intervals of two to three weeks. In other words each value is the average of four entirely independent tests.

The original plan called for a 1:7 mix, but it was found impracticable to handle the specimens containing tannic acid, consequently this mix was dropped.

[1]Concrete is here used in its general sense to include what are generally considered mortar mixtures.

Materials.—The Portland cement used in this investigation consisted of a mixture of equal parts of four brands purchased in the Chicago market. Lots of one sack of each brand of cement were thoroughly mixed dry in a concrete mixer before it was used. Miscellaneous tests of cement are given in Table 1. Compression and tension tests of standard sand mortar at ages up to two years are given in Table 2.

TABLE 1.—MISCELLANEOUS TESTS OF CEMENT.

A mixture of equal parts of four brands of Portland cement, purchased in the Chicago market. All tests were made in accordance with the standard methods of the American Society for Testing Materials. Each value is the average of two tests.

Fineness Residue on No. 200 Sieve	Normal Consistency, per cent by weight	Time of Setting				Soundness Test Over Boiling Water
		Vicat Needle		Gillmore Needle		
		Initial h. m.	Final h. m.	Initial h. m.	Final h. m.	
18.8	23.0	3 40	7 40	5 15	8 30	OK

TABLE 2.—MORTAR STRENGTH TESTS.

1 : 3 Standard sand mortar. Stored in water; tested wet. Each value is the average of 5 tests made on different days.

Mixing Water, per cent	Briquettes Tensile Strength, lb. per sq. in.						2 by 4-in. Cylinders Compressive Strength, lb. per sq. in.					
	7 d.	28 d.	3 m.	6 m.	1 y.	2 y.	7 d.	28 d.	3 m.	6 m.	1 y.	2 y.
10.3	242	378	462	440	387	369	1770	3360	4380	4570	4490	4650

The aggregates consisted of different sizes of sand and pebbles from the Elgin, Ill., pit of the Chicago Gravel Company. The material was largely of limestone origin. Sieve analysis of the aggregates is given in Table 3. The "fineness modulus"[1] of the aggregate is used as a measure of its size and grading. It is the sum of the percentages in the sieve analysis divided by 100. The sieve analysis is expressed in terms of the percentages by weight *coarser than* the sieves shown. The sieves are from the standard screen scale series of The W. S. Tyler Co., Cleveland, Ohio.

The tannic acid used was of commercial grade in crystal form. It was dissolved in water and applied in small increments to the sand by sprinkling a known solution over the sand and mixing thoroughly. The sand was allowed to dry at a low temperature before another application was made. Tannic acid was added as a surface coating in this way to the amount of 0.05, 0.10, 0.20 and 0.40 per cent of the weight of the aggregate.

[1] For further details see "Design of Concrete Mixtures" by Duff A. Abrams, *Bulletin 1*. Structural Materials Research Laboratory, Lewis Institute, Chicago.

The sands thus prepared responded to the "colorimetric test" with sodium hydroxide described below.

The water was from the city supply obtained from Lake Michigan.

Test Pieces.—All tests were made on 3 by 6-in. cylinders. The concrete was mixed by hand in batches of sufficient size to make 5 specimens. One specimen from each batch was tested at 7 days, 28 days, 3 months, 1 year, and 2 years. The specimens were molded in metal forms consisting of 6-in. lengths of cold-drawn steel tubing which was split along one element and closed by means of a circumferential band. The concrete was placed in the form in 3 or 4 layers; each layer being puddled with a small steel bar. The different mixtures and sizes of aggregate were mixed to the same consistency. One batch of each kind was mixed before starting on the second round.

The forms were removed on the day following molding. The specimens were stored in damp sand until the time of test.

DATA OF TESTS.

The data of the concrete tests are given in Tables 4 and 5. Each value for concrete strength is the average of four independent tests made on different days. In Table 6 the strengths of concrete containing tannic acid have been reduced to percentages of the strength of similar concrete without tannic acid and tested at the same age; in this table the tannic acid is given in terms of the mixing water (per cent concentration). Most of the results are given in graphical form in Fig. 1 to 16.

The unit weight of the concrete upon removal of the forms is given in Table 7.

TABLE 3.—MISCELLANEOUS TESTS OF AGGREGATE.

Sand pebbles from Elgin, Ill.
The sieves used were from the "Standard Screen Scale," manufactured by The W. S. Tyler Co., Cleveland

Size of Aggregate	Weight, lb. per cu. ft.	Sieve Analysis per cent coarser than each sieve								Fineness Modulus**
		100	48*	28*	14*	8	4	⅜-in.	¾-in.	
0 to No. 28*	100	97	76	0	.....	.....	.....	.....	.....	1.73
0 to No. 14*	104	98	84	33	0	.....	.....	.....	.....	2.15
0 to No. 8	110	98	86	49	22	0	.....	.....	.....	2.55
0 to No. 4	115	99	88	58	35	20	0	.....	.....	3.00
0 to ⅜ in.	120	99	91	70	52	36	20	0	.....	3.68
0 to ¾ in.	127	99	93	75	60	52	40	22	0	4.40

*(Note added at Second Printing, November, 1922.) The No. 48, 28, and 14-mesh sieves give the same separation as the No. 50, 30, and 16 now used in the "Tentative Method of Test for Sieve Analysis of Aggregates for Concrete" of the American Society for Testing Materials. The No. 50, 30, and 16 sieves are now used in all our tests.

**The sum of percentages in sieve analysis, divided by 100.

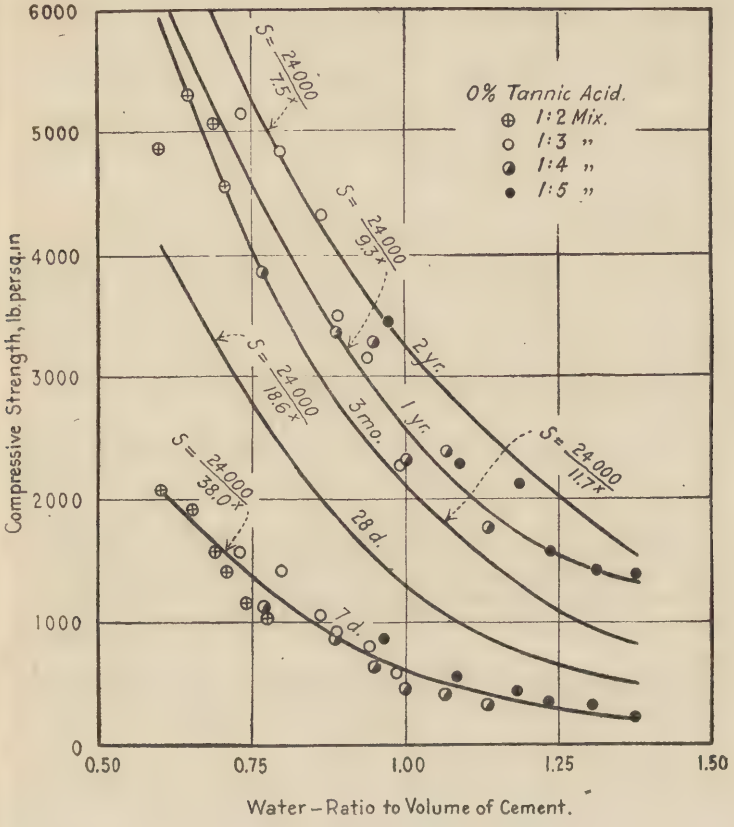


FIG. 1.—WATER-RATIO STRENGTH RELATION FOR CONCRETE WITHOUT TANNIC ACID.

Each value is the average of 4 tests made on different days.
Points are shown for 7-day and 1-year tests only.
Compare Fig. 2 and 3.

TABLE 4.—EFFECT OF TANNIC ACID ON THE STRENGTH OF CONCRETE. (Mixes 1:2 and 1:3)

Compression tests of 3 by 6-in. concrete cylinders.
Aggregate sand and pebbles from Elgin, Ill.
Hand-mixed concrete. Relative consistency, 1.00.
Specimens were mixed 5 in a batch, one for test at each age.
In general, each value is the average of 4 tests made on different days.

Aggregate		Mix, 1:2 by Volume							Mix, 1:3 by Volume						
Size	F.M.[1]	Water-Ratio.	Compressive Strength, lb. per sq. in.						Water-Ratio.	Compressive Strength, lb. per sq. in.					
			7 d.	28 d.	3 m.	1 y.	2 y.	Average.		7 d.	28 d.	3 m.	1 y.	2 y.	Average.
0.0 PER CENT TANNIC ACID															
0 to No. 28	1.73	0.77	1050	2170	3200	3800	4500	2940	0.98	610	1220	2280	2300	3730	2030
0 to No. 14	2.15	0.74	1150	2410	2870	3440	4740	2920	0.94	800	1640	2430	3150	4080	2420
0 to No. 8	2.55	0.71	1370	2630	3780	4580	4700	3410	0.89	890	1840	2790	3500	4180	2640
0 to No. 4	3.00	0.69	1600	3270	4050	5040	5600	3910	0.86	1090	2230	3860	4340	5100	3320
0 to ⅜ in.	3.68	0.65	1910	3700	5140	5310	5830	4380	0.80	1440	2860	4620	4850	5570	3870
0 to ¾ in.	4.40	0.60	2100	3910	5020	4870	5450	4270	0.73	1600	3340	4690	5150	6030	4160
Average			1530	3020	4010	4510	5140	3640		1070	2220	3440	3880	4780	3070
0.05 PER CENT TANNIC ACID[2]															
0 to No. 28	1.73	0.77	1050	2040	3510	3960	4350	2980	0.98	580	1250	2000	2620	3300	1950
0 to No. 14	2.15	0.74	1200	2390	3640	4660	4640	3310	0.94	660	1350	2190	2960	3640	2160
0 to No. 8	2.55	0.71	1200	2370	3730	4200	4400	3180	0.89	740	1490	2380	3330	3870	2360
0 to No. 4	3.00	0.69	1370	3000	3880	4290	5100	3530	0.86	940	1990	3060	3830	4650	2890
0 to ⅜ in.	3.68	0.65	1520	2620	4070	4470	5600	3660	0.80	1010	2240	3290	4110	4740	3080
0 to ¾ in.	4.40	0.60	1640	2770	3940	4070	5000	3480	0.73	1160	2350	3570	3720	4760	3110
Average			1330	2530	3800	4270	4850	3360		850	1780	2750	3430	4160	2590
0.10 PER CENT TANNIC ACID[2]															
0 to No. 28	1.73	0.77	880	1880	3170	3470	4290	2740	0.98	450	1010	1460	2380	2880	1640
0 to No. 14	2.15	0.74	920	1960	3370	3790	4500	2910	0.94	600	1330	1920	2670	3140	1930
0 to No. 8	2.55	0.71	990	2180	3350	3990	4820	3070	0.89	630	1420	2030	2490	3560	2030
0 to No. 4	3.00	0.69	1080	2120	3560	2870	4640	2850	0.86	570	1270	2380	3120	3480	2160
0 to ⅜ in.	3.68	0.65	1410	2700	4090	4120	5510	3570	0.80	820	1870	2960	3450	4160	2650
0 to ¾ in.	4.40	0.60	1360	2830	3940	4120	5320	3510	0.73	890	2000	3070	3140	4500	2720
Average			1110	2280	3580	3730	4850	3110		660	1480	2300	2870	3620	2190
0.20 PER CENT TANNIC ACID[2]															
0 to No. 28	1.73	0.77	720	1570	2790	3120	4230	2490	0.98	340	820	1280	1930	2400	1350
0 to No. 14	2.15	0.74	850	1650	2520	3540	3470	2410	0.94	440	1080	1650	2350	2850	1670
0 to No. 8	2.55	0.71	970	1880	2780	3810	4520	2790	0.89	420	1090	1590	2110	2720	1590
0 to No. 4	3.00	0.69	990	2000	3090	3640	4920	2930	0.86	500	1190	2020	2700	3490	1980
0 to ⅜ in.	3.68	0.65	1260	2420	3440	3670	3960	2950	0.80	600	1540	2340	2600	3740	2160
0 to ¾ in.	4.40	0.60	1250	2500	3220	3640	4580	3040	0.73	760	1460	2160	2730	3620	2150
Average			1010	2000	2970	3570	4280	2770		510	1200	1840	2400	3140	1820
0.40 PER CENT TANNIC ACID[2]															
0 to No. 28	1.73	0.77	530	1370	2000	3300	3350	2110	0.98	90	540	730	1430	1860	930
0 to No. 14	2.15	0.74	680	1330	1890	2890	3200	2000	0.94	200	720	810	1440	1900	1010
0 to No. 8	2.55	0.71	660	1480	2220	3120	3860	2270	0.89	220	750	950	1410	2060	1080
to No. 4	3.00	0.69	920	1710	2680	3120	3690	2420	0.86	460	1120	1580	2200	3010	1670
o ⅜ in.	3.68	0.65	1180	2040	2720	3360	3970	2650	0.80	430	1130	1860	2620	3270	1860
¾ in.	4.40	0.60	1040	2130	2510	2920	3500	2420	0.73	500	1310	1940	2310	3100	1830
erage			840	1680	2340	5120	3600	2310		320	930	1310	1900	2530	1400

[1] Fineness modulus of aggregate; see Table 3.
[2] Table 6 gives the *concentration* of tannic acid in terms of the weight of mixing water.

TABLE 5.—EFFECT OF TANNIC ACID ON THE STRENGTH OF CONCRETE. (Mixes 1:4 and 1:5)

Compression tests of 3 by 6-in. concrete cylinders.
Aggregate sand and pebbles from Elgin, Ill.
Hand-mixed concrete. Relative consistency, 1.00.
Specimens were mixed 5 in a batch, one for test at each age.
In general, each value is the average of 4 tests made on different days.

Aggregate		Mix, 1 : 4 by Volume							Mix, 1 : 5 by Volume						
Size	F.M.[1]	Water-Ratio.	Compressive Strength, lb. per sq. in.						Water-Ratio.	Compressive Strength, lb. per sq. in.					
			7 d.	28 d.	3 m.	1 y.	2 y.	Average.		7 d.	28 d.	3 m.	1 y.	2 y.	Average.
0.0 PER CENT TANNIC ACID															
0 to No. 28	1.73	1.13	360	760	1410	1760	2480	1350	1.38	230	500	820	1390	1600	910
0 to No. 14	2.15	1.07	410	910	1600	2390	2600	1580	1.31	290	610	1040	1410	1630	1000
0 to No. 8	2.55	1.00	460	1000	1700	2320	2660	1630	1.23	340	750	1170	1590	1970	1160
0 to No. 4	3.00	0.95	630	1270	2360	3200	3810	2250	1.18	450	920	1550	2140	2570	1530
0 to ⅜ in.	3.68	0.88	840	1700	3220	3390	4140	2660	1.09	570	1220	1920	2350	3300	1870
0 to ¾ in.	4.40	0.77	1080	2210	3440	3810	4990	3110	0.97	890	1770	2870	3430	4400	2670
Average			630	1310	2290	2810	3450	2100		460	960	1560	2050	2580	1520
0.05 PER CENT TANNIC ACID[2]															
0 to No. 28	1.73	1.13	370	730	1290	1960	2260	1320	1.38	180	480	800	1010	1410	780
0 to No. 14	2.15	1.07	320	790	1520	1950	2520	1420	1.31	240	500	830	1300	1600	890
0 to No. 8	2.55	1.00	470	890	1680	2160	2450	1530	1.23	260	600	900	1490	1700	990
0 to No. 4	3.00	0.95	480	1180	2020	2700	3320	1940	1.18	350	710	1300	1880	2220	1290
0 to ⅜ in.	3.68	0.88	550	1330	2110	2950	3230	2030	1.09	380	970	1420	2090	2620	1500
0 to ¾ in.	4.40	0.77	780	1550	2690	3380	3840	2450	0.97	550	1200	2070	2450	3350	1920
Average			500	1080	1880	2520	2940	1780		330	740	1220	1700	2150	1230
0.10 PER CENT TANNIC ACID[2]															
0 to No. 28	1.73	1.13	170	640	880	1530	1740	990	1.38	130	400	630	1090	1450	740
0 to No. 14	2.15	1.07	340	730	1280	1890	2230	1290	1.31	200	460	760	1100	1540	810
0 to No. 8	2.55	1.00	320	750	1360	2160	2580	1430	1.23	210	420	910	1180	1600	860
0 to No. 4	3.00	0.95	380	910	1730	2620	2720	1670	1.18	240	620	950	1440	1470	940
0 to ⅜ in.	3.68	0.88	560	1060	2020	3140	2600	1880	1.09	310	840	1320	1780	2460	1340
0 to ¾ in.	4.40	0.77	760	1170	2480	3030	2670	2020	0.97	500	1020	1660	1970	2290	1490
Average			420	880	1620	2390	2420	1550		260	630	1040	1430	1800	1030
0.20 PER CENT TANNIC ACID[2]															
0 to No. 28	1.73	1.13	250	480	850	1680	1730	1000	1.38	130	320	460	750	1290	590
0 to No. 14	2.15	1.07	420	610	1030	1370	2030	1090	1.31	150	290	520	820	1030	560
0 to No. 8	2.55	1.00	470	840	1350	1770	2120	1310	1.23	170	460	580	1020	1280	700
0 to No. 4	3.00	0.95	300	940	1670	2140	2190	1450	1.18	250	370	680	800	1940	810
0 to ⅜ in.	3.68	0.88	360	930	1490	2140	2500	1480	1.09	200	490	890	1120	1650	870
0 to ¾ in.	4.40	0.77	380	970	2200	2660	2910	1820	0.97	240	670	1020	1490	2000	1080
Average			360	800	1430	1960	2250	1360		190	430	690	1000	1530	770
0.40 PER CENT TANNIC ACID[2]															
0 to No. 28	1.73	1.13	310	540	700	1050	1560	830	1.38	70*a*	190*a*	780	610	1150	560
0 to No. 14	2.15	1.07	230	450	840	1030	1950	900	1.31	90	220	420	920	1190	570
0 to No. 8	2.55	1.00	140	480	910	1290	1820	930	1.23	80	210	440*a*	*a*850	1230*a*	560
0 to No. 4	3.00	0.95	340	1070	1520	1900	2780	1520	1.18	100	300	480	870	1260	600
0 to ⅜ in.	3.68	0.88	410	1020	1640	1940	2260	1450	1.09	160	510	740	980	1500	780
0 to ¾ in.	4.40	0.77	440	1060	1440	1890	2340	1430	0.97	200	580	960	1350	1490	920
Average			310	770	1180	1520	2120	1180		120	340	640	930	1300	670

[1] Fineness modulus of aggregate; see Table 3.
[2] Table 6 gives the *concentration* of tannic acid in terms of the weight of mixing water
a Values interpolated on account of disintegration of some of the specimens.

DISCUSSION OF TESTS.

The methods followed in making these tests gave consistent results throughout the series. While it is impracticable to deal with one phase of this subject to the exclusion of all others, the results of the tests will be discussed under a number of different headings. It should be understood, however, that all of these topics were studied in the same tests; consequently there is of necessity some overlapping in the discussion.

Effect of Quantity of Mixing Water.—The effect of water is mentioned first, due to the fundamental influence of this factor on the strength and

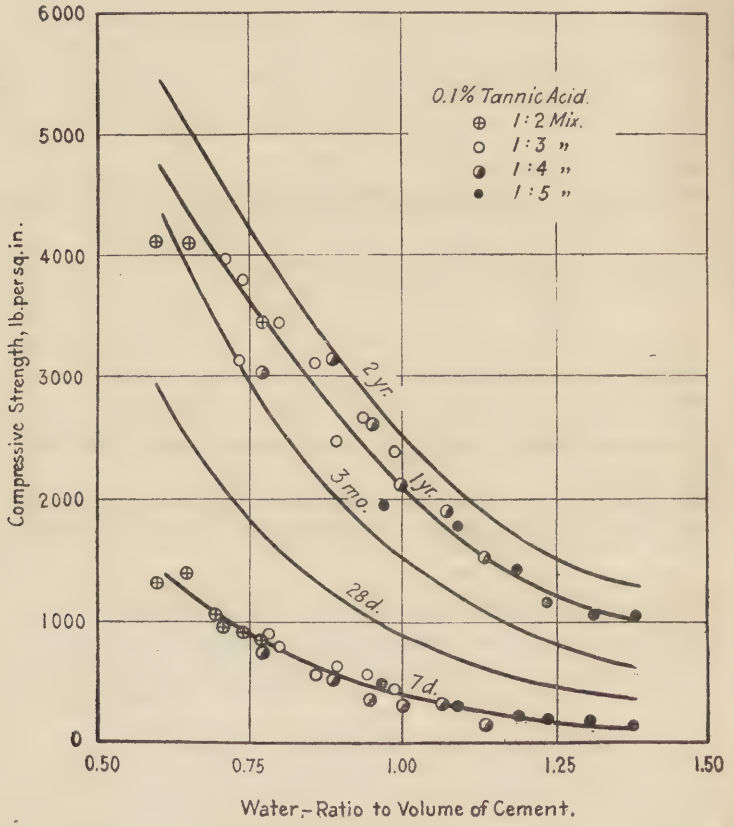


FIG. 2.—WATER-RATIO STRENGTH RELATION FOR CONCRETE WITH 0.10 PER CENT TANNIC ACID.

Each value is the average of 4 tests made on different days.
Points are shown for 7-day and 1-year tests only.
Compare Fig. 1 and 3.

TABLE 6.—EFFECT OF TANNIC ACID ON THE STRENGTH OF CONCRETE.

Data as in Tables 4 and 5, expressed as percentage of strength of concrete from clean aggregate.

Size of Aggregate	Tannic Acid		Per Cent of Strength of Concrete with Clean Aggregates						Tannic Acid		Per Cent of Strength of Concrete with Clean Aggregates					
	(1)	(2)	7 d.	28 d.	3 m.	1 y.	2 y.	Average	(1)	(2)	7 d.	28 d.	3 m.	1 y.	2 y.	Average
Mix, 1 : 2 by Volume									**Mix, 1 : 3 by Volume**							
0 to No. 28	0.05	0.21	100	110	103	96		101	0.05	0.24	95	103	88	114	89	98
0 to No. 14	....	0.23	102	99	126	136	98	112	....	0.27	82	82	90	94	89	87
0 to No. 8	....	0.25	88	90	98	92	94	92	....	0.30	83	81	86	94	93	87
0 to No. 4	....	0.27	86	92	96	85	91	90	....	0.32	87	89	79	88	91	87
0 to ⅜ in.	....	0.30	80	71	79	84	96	82	....	0.36	71	78	71	85	85	78
0 to ¾ in.	....	0.34	78	71	79	84	92	81	....	0.42	73	71	76	72	79	74
Average	....	0.27	89	86	98	97	94	93	....	0.32	82	84	82	91	88	85
0 to No 28	0.10	0.42	84	86	99	91	95	91	0.10	0.49	74	82	64	104	78	80
0 to No. 14	....	0.46	80	81	118	110	95	97	....	0.53	75	81	79	85	77	79
0 to No. 8	....	0.50	73	83	89	87	103	87	....	0.59	71	77	73	71	85	75
0 to No. 4	....	0.54	68	65	88	57	83	72	....	0.64	52	57	62	72	68	62
0 to ⅜ in.	....	0.60	74	73	79	77	95	80	....	0.72	57	66	64	71	75	67
0 to ¾ in.	....	0.68	65	72	79	85	98	80	....	0.84	56	60	66	61	74	63
Average	....	0.53	74	77	92	84	95	84	....	0.64	64	70	68	77	76	71
0 to No. 28	0.20	0.84	68	72	87	82	94	81	0.20	0.98	56	67	56	84	65	66
0 to No. 14	....	0.92	74	68	87	103	73	81	....	1.06	55	66	68	74	70	67
0 to No. 8	....	1.00	71	71	74	83	96	79	....	1.18	47	59	57	61	65	58
0 to No. 4	....	1.08	62	61	76	72	88	72	....	1.28	46	54	52	62	68	56
0 to ⅜ in.	....	1.20	66	65	57	69	68	67	....	1.44	42	54	51	54	67	54
0 to ¾ in.	....	1.38	59	64	64	75	84	69	....	1.68	48	44	46	53	60	50
Average	....	1.07	67	67	76	81	84	75	....	1.27	49	57	55	65	66	58
0 to No. 28	0.40	1.66	51	63	62	87	74	67	0.40	1.96	15	44	32	62	53	41
0 to No. 14	....	1.84	59	55	66	84	68	66	....	2.12	25	44	33	46	46	39
0 to No. 8	....	2.00	48	56	59	68	82	63	....	2.36	25	41	34	40	49	38
0 to No. 4	....	2.16	57	52	66	62	66	61	....	2.56	42	50	41	51	59	49
0 to ⅜ in.	....	2.40	62	55	53	63	68	60	....	2.88	30	39	40	54	59	44
0 to ¾ in.	....	2.76	49	54	50	60	64	55	....	3.36	31	39	41	45	51	41
Average	....	2.14	54	56	59	71	70	62	....	2.54	28	43	37	50	53	42
Mix, 1 : 4 by Volume									**Mix, 1 : 5 by Volume**							
0 to No. 28	0.05	0.28	103	96	92	111	91	99	0.05	0.29	78	96	98	72	88	86
0 to No. 14	....	0.31	78	87	95	82	97	88	....	0.32	83	82	80	92	98	87
0 to No. 8	....	0.35	102	89	99	93	92	95	....	0.36	77	80	77	94	86	83
0 to No. 4	....	0.39	76	93	86	85	87	85	....	0.39	78	77	84	88	90	83
0 to ⅜ in.	....	0.44	66	77	66	87	78	75	....	0.44	61	79	74	89	79	76
0 to ¾ in.	....	0.53	72	70	78	89	77	77	....	0.53	62	68	72	71	76	70
Average	....	0.38	83	85	86	91	87	86	....	0.39	73	80	81	84	86	81
0 to No. 28	0.10	0.57	47	84	63	87	70	70	0.10	0.58	57	80	77	78	90	76
0 to No. 14	....	0.62	83	80	80	79	86	82	....	0.64	69	75	73	78	94	78
0 to No. 8	....	0.70	70	75	80	93	97	83	....	0.72	62	56	78	74	81	70
0 to No. 4	....	0.78	61	72	73	82	71	72	....	0.78	53	67	61	67	57	61
0 to ⅜ in.	....	0.88	67	62	62	93	63	69	....	0.88	54	69	68	76	74	68
0 to ¾ in.	....	1.06	70	53	72	79	54	66	....	1.05	56	58	58	57	52	56
Average	....	0.77	66	71	72	86	74	74	....	0.78	58	68	69	72	75	68
0 to No. 28	0.20	1.14	70	63	60	95	70	72	0.20	1.16	57	64	56	54	80	62
0 to No. 14	....	1.24	102	67	64	57	78	74	....	1.28	52	48	50	58	63	54
0 to No. 8	....	1.41	102	84	79	76	79	84	....	1.44	50	61	50	64	65	58
0 to No. 4	....	1.56	48	74	71	67	57	63	....	1.56	56	40	44	37	76	51
0 to ⅜ in.	....	1.76	43	54	46	63	61	53	....	1.76	35	40	46	48	50	44
0 to ¾ in.	....	2.12	35	44	64	70	58	54	....	2.10	27	38	35	43	45	38
Average	....	1.54	67	61	64	71	67	67	....	1.55	46	48	47	51	63	51
0 to No. 28	0.40	2.28	86	71	50	60	63	66	0.40	2.32	31	38	95	44	72	56
0 to No. 14	....	2.48	56	49	52	43	75	55	....	2.56	31	36	40	65	73	49
0 to No. 8	....	2.82	30	48	54	56	68	51	....	2.88	24	28	38	54	62	41
0 to No. 4	....	3.12	54	85	64	59	73	67	....	3.12	22	33	31	41	49	35
0 to ⅜ in.	....	3.52	49	61	51	57	55	55	....	3.52	28	42	39	42	45	39
0 to ¾ in.	....	4.24	41	48	42	50	47	46	....	4.20	22	33	33	39	34	32
Average	....	3.08	53	60	52	54	64	57	....	3.10	26	35	46	48	56	42

(1) Tannic acid per cent of weight of aggregate. (2) Per cent of weight of mixing water (concentration)

other properties of the concrete. The quantity of water used is expressed in terms of the "water-ratio" which is obtained by dividing the volume of water by the (loose) volume of the cement in the batch. Cement is considered as weighing 94 lb. per cu. ft. A rich mix will have a lower "water-ratio" than a lean one if the same aggregate is used and the concrete is mixed to a uniform plasticity. The quantity of water used may be expressed in terms of gallons per sack of cement.

Fig. 1 to 3 show the relation between the water-ratio and the compressive strength at different ages for concrete without tannic acid and with 0.1 and 0.4 per cent tannic acid. Similar sets of curves may be drawn for 0.05 and 0.2 per cent tannic acid. The individual points are platted for 7-day and 1-year tests only. These figures show:

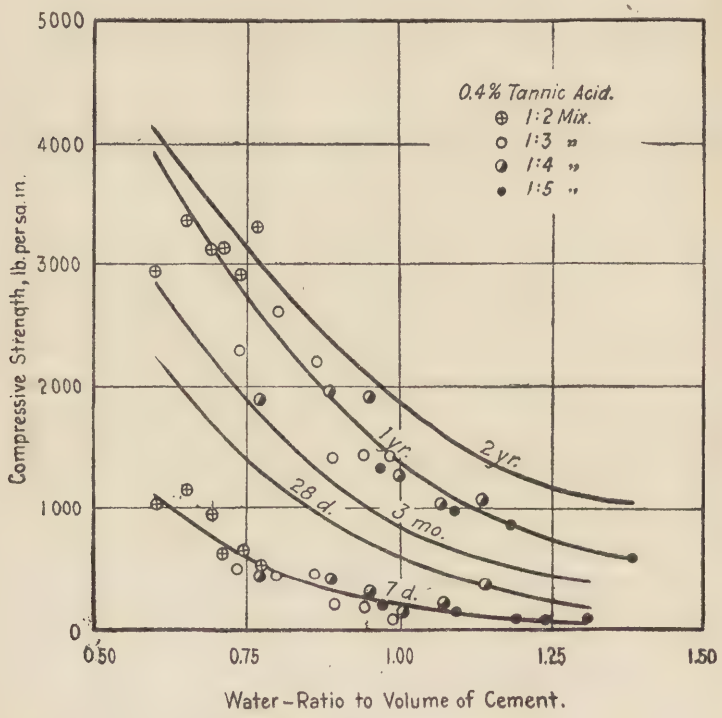


FIG. 3.—WATER-RATIO STRENGTH RELATION FOR CONCRETE WITH 0.40 PER CENT TANNIC ACID.

Each value is the average of 4 tests made on different days.
Points are shown for 7-day and 1-year tests only.
Compare Fig. 1 and 2.

1. The age of the concrete and the presence of tannic acid change the strength of the concrete, but the same type of relation is preserved for all conditions.

2. The strength of the concrete is rapidly reduced with the increase in water-ratio for all ages and all percentages of tannic acid.

3. A constant relation exists between strength of concrete and the water-ratio, regardless of mix or size and grading of aggregate.

4. The more tannic acid used, the lower the strength of the concrete for all mixes, ages and sizes of aggregate.

The tests in this series confirm the results of many other investigations carried out in this Laboratory in showing that the water-ratio determines the strength of the concrete, so far as the quantity of cement and the size and grading of aggregate are concerned, and so long as the concrete is plastic and the aggregate is not graded too coarse for the quantity of cement used. The water-ratio-strength curves for these tests are of the form:

$$S = \frac{A}{B^x} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where S = compressive strength of concrete and x = water-ratio of mix (an exponent). A and B are constants which depend on the quality of the cement and the conditions of the test.

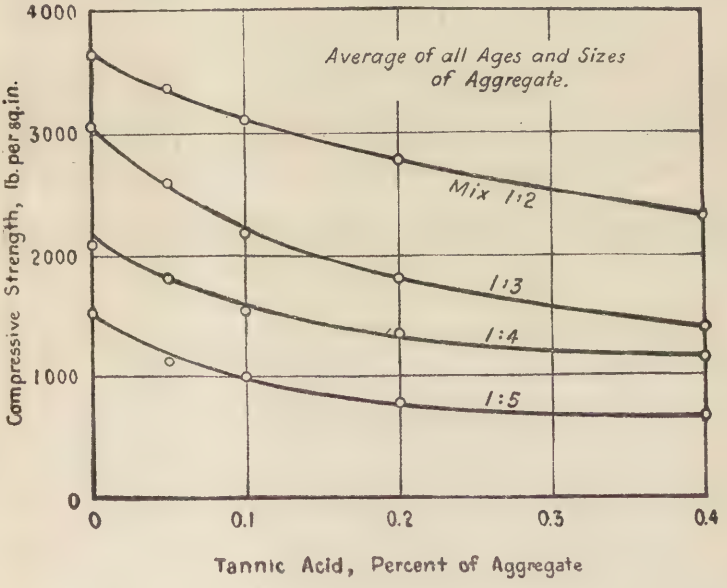


FIG. 4.—EFFECT OF TANNIC ACID ON THE STRENGTH OF CONCRETE OF DIFFERENT MIXTURES.

In general, the values are the average of 120 tests from 6 sizes of aggregate and 5 ages. Compare Fig. 5.

The 28-day tests without tannic acid (Fig. 1) conform to the relation expressed by the equation:

$$S = \frac{24000}{18.6^x} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

The corresponding equations for other ages are given in Fig. 1. Equations of similar form may be derived for other percentages of tannic acid. The relation between strength and water-ratio for specimens with 0.10 per cent and 0.40 per cent of tannic acid is platted in Fig. 2 and 3.

Certain other series of concrete tests made in this Laboratory conform more closely to a curve of somewhat different type, which, however, gives essentially the same values for the usual range of concrete mixtures. The

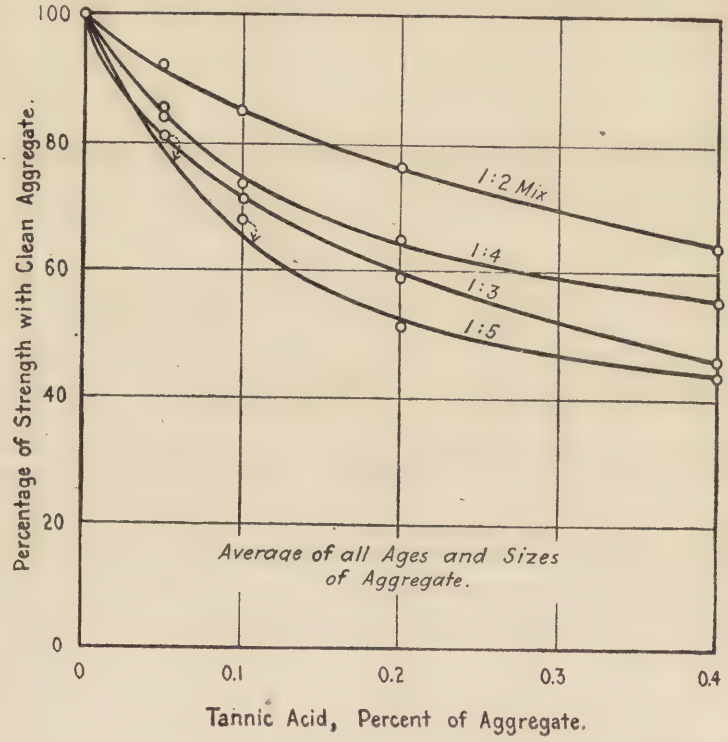


FIG. 5.—EFFECT OF TANNIC ACID ON THE STRENGTH OF CONCRETE OF DIFFERENT MIXTURES.

Same data as in Fig. 4, except that values are expressed as percentages of the strength of concrete made from clean aggregates. Fig. 6 shows the same data in a different form.

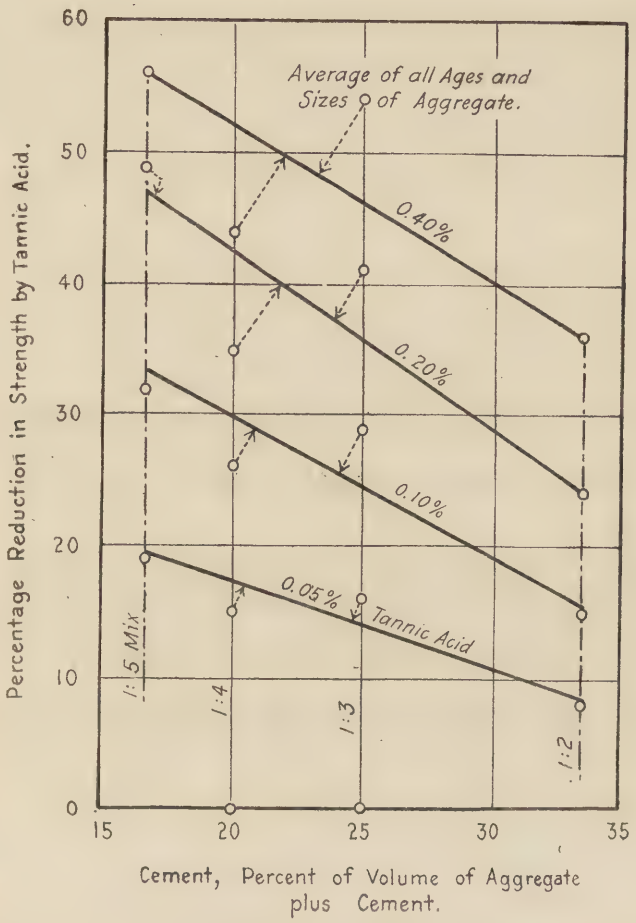


FIG. 6.—REDUCTION IN STRENGTH OF CONCRETE OF DIFFERENT MIXTURES BY TANNIC ACID.

In general, the values are the average of 120 tests from 6 sizes of aggregate and 5 ages. Compare Fig. 5.

type of the curve is of minor importance; the significant feature is that the water-ratio determines the strength of the concrete for given materials.

Effect of Quantity of Tannic Acid.—The effect of quantity of tannic acid is shown in a number of the figures. In Fig. 4 the effect of tannic acid is shown for each mix. All ages and sizes of aggregates have been averaged. It will be seen by reference to Fig. 9 that the age of the concrete has only a slight effect. Each point in Fig. 4 represents 120 tests from 5 ages and 6 sizes of aggregate. In Fig. 5 the same tests are platted using the average strength without tannic acid as 100 per cent. It will be noted that

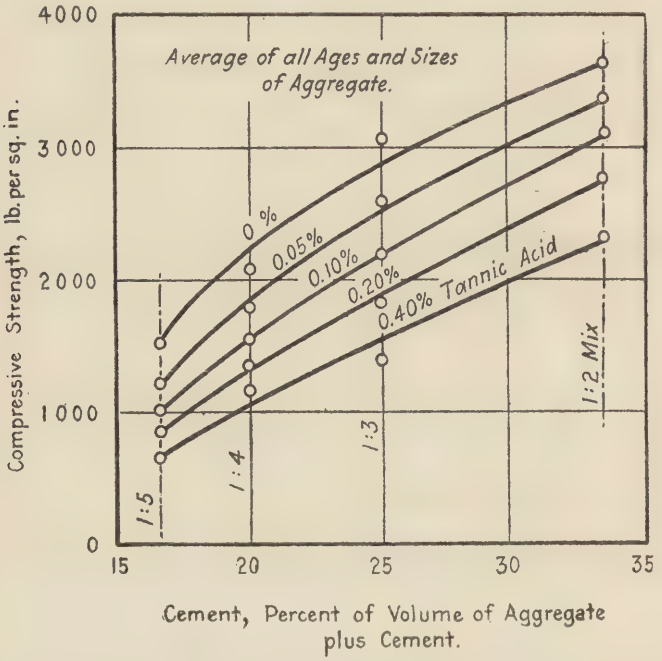


FIG. 7.—EFFECT OF QUANTITY OF CEMENT ON THE STRENGTH OF CONCRETE.

In general, the values are the average of 120 tests from 6 sizes of aggregate and 5 ages.

the curves are similar for all mixes, although the reduction in strength due to the presence of tannic acid is considerably greater for the lean than for the rich mixtures. Very small percentages of tannic acid as a surface coating on the aggregate have the effect of materially reducing the strength of concrete for all mixes covered by these tests. Less than 0.1 per cent in terms of the weight of the aggregate may reduce the strength to one-half its original value. For the 1:4 mix the strength was reduced about 15 per cent for 0.05 per cent tannic acid; about 33 per cent for 0.10 per cent tannic acid; and nearly 50 per cent for 0.40 per cent tannic acid.

These tests confirm the results of earlier experiments made in this Laboratory so far as the quantitative effect of organic impurities is concerned.

Effect of Quantity of Cement.—These tests give information on the effect of quantity of cement on the strength of concrete with and without tannic acid. Fig. 4 and 5 discussed above show the effect of the quantity of cement as expressed by the mix. In Fig. 7 the results of the tests are platted with reference to the percentage of cement in the batch. Fig. 6 shows the average *reduction* in strength for different percentages of tannic acid. The quantity of cement is expressed as a percentage of the volume

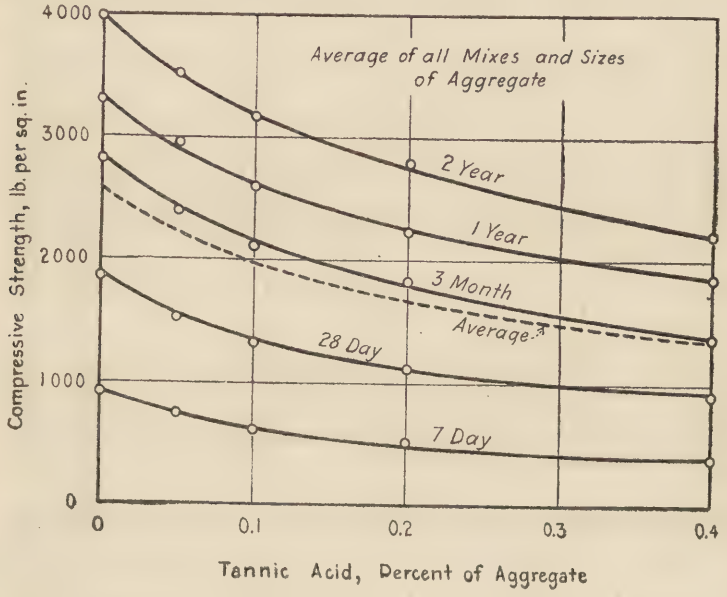


FIG. 8.—EFFECT OF TANNIC ACID ON THE STRENGTH OF CONCRETE AT DIFFERENT AGES.

In general, the values are the average of 96 tests from 4 mixes and 6 sizes of aggregate. Compare Fig. 9.

of the cement plus aggregate. A 1:4 mix contains 20 per cent cement on this basis; a neat cement mix would be 100 per cent.

The rich mixtures are less affected by tannic acid than the lean ones. A 1:5 mix was reduced in strength 33 per cent by 0.10 per cent tannic acid; the reduction for 1:4, 1:3 and 1:2 mixes was 30, 25 and 15 per cent, respectively, for the same quantity of tannic acid. It should be noted that these are average values of all ages and sizes of aggregate. There are somewhat less important differences in strength due to the age of the concrete and the size of aggregate as shown in Fig. 9 and 10. As indicated

in Table 5, some of the 1:5 mixes with finer sands disintegrated before the time of test. It was impossible to remove the 1:7 mixes from the molds without breakage.

Effect of Size of Aggregate.—The size and grading of the aggregate is conveniently measured by its fineness modulus. In Fig. 10 the relation of strength to tannic acid is shown for each size of aggregate. In this

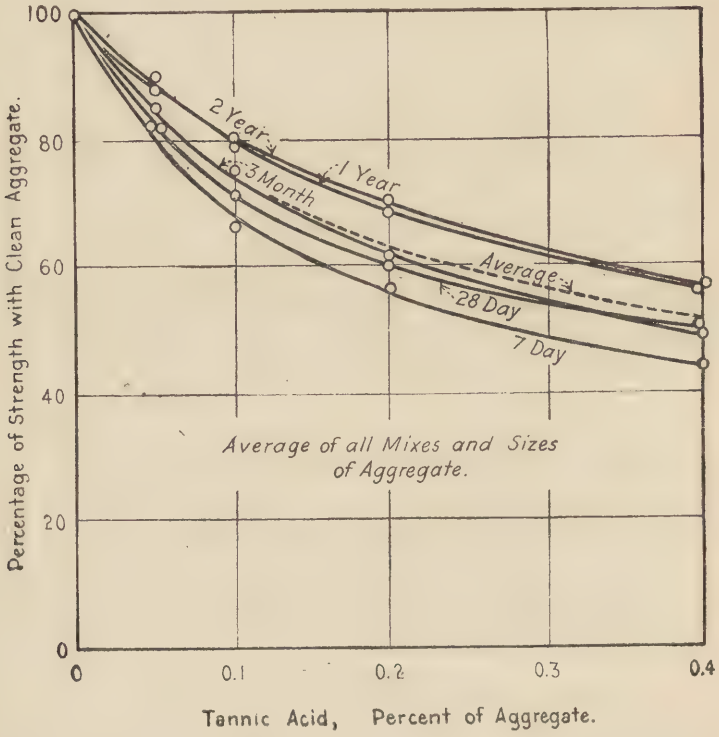


FIG. 9.—EFFECT OF TANNIC ACID ON THE STRENGTH OF CONCRETE.

Same data as in Fig. 8, except that values are expressed as percentages of the strength of concrete made from clean aggregates. Fig. 15 shows the same data in a different form.

diagram, mixes ranging from 1:5 to 1:2, and ages at test ranging from 7 days to 2 years have been averaged. The reduction in strength for each percentage of tannic acid is shown in Fig. 11. The finer sizes of sand are less affected than the coarser sizes; the coarser aggregates suffer about 20 per cent greater reduction in strength than the finest sand.

Fig. 12 shows the relation between the fineness modulus and the compressive strength of the concrete; a separate curve is drawn for each

percentage of tannic acid. For the aggregate gradings used, the strength of the concrete increased with the fineness modulus of the aggregate for all mixes and percentages of tannic acid. These curves bear out the results of other tests made in this Laboratory with reference to the use of the

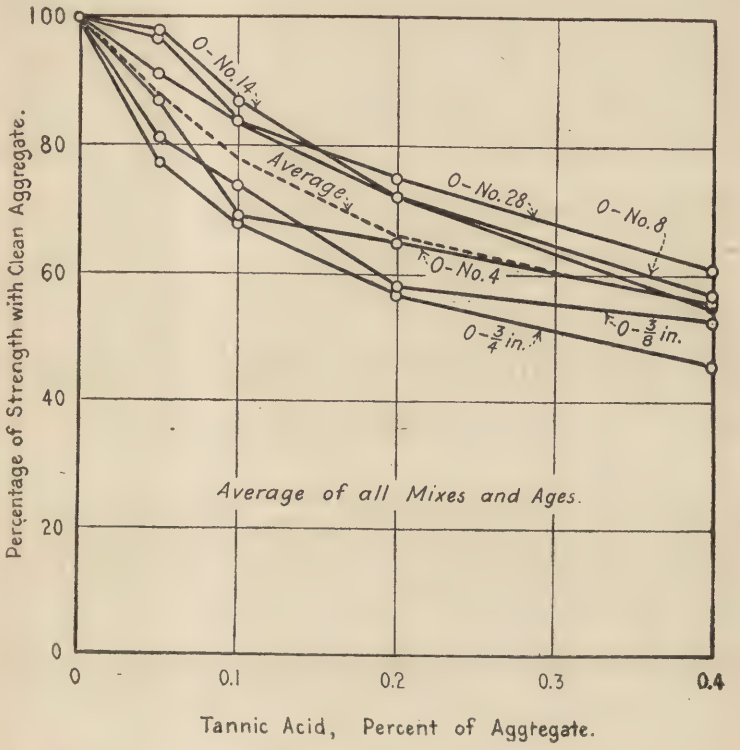


FIG. 10.—EFFECT OF TANNIC ACID ON THE STRENGTH OF CONCRETE MADE OF AGGREGATES OF DIFFERENT GRADINGS.

Values are expressed as percentages of strength of concrete made from clean aggregates. In general, each value is the average of 80 tests from 4 mixes and 5 ages. Fig. 11 shows the same data in a different form.

fineness modulus as a measure of the size and grading of aggregates. It was pointed out in Bulletin 1, "Design of Concrete Mixtures," that the fineness modulus may be considered as a measure of the quantity of water required to produce a concrete of uniform workability. Since the water content dictates the strength of concrete, the fineness modulus gives a satisfactory method of dealing with strength also.

General Discussion of Effect of Tannic Acid on the Strength of Concrete.—Fig. 16 shows the relation between the concentration of an aqueous solution of tannic acid and the strength of the concrete expressed as a percentage of the strength of concrete containing no tannic acid. Only the 28-day tests are platted. Similar curves may be drawn for other ages from the values given in Table 6.

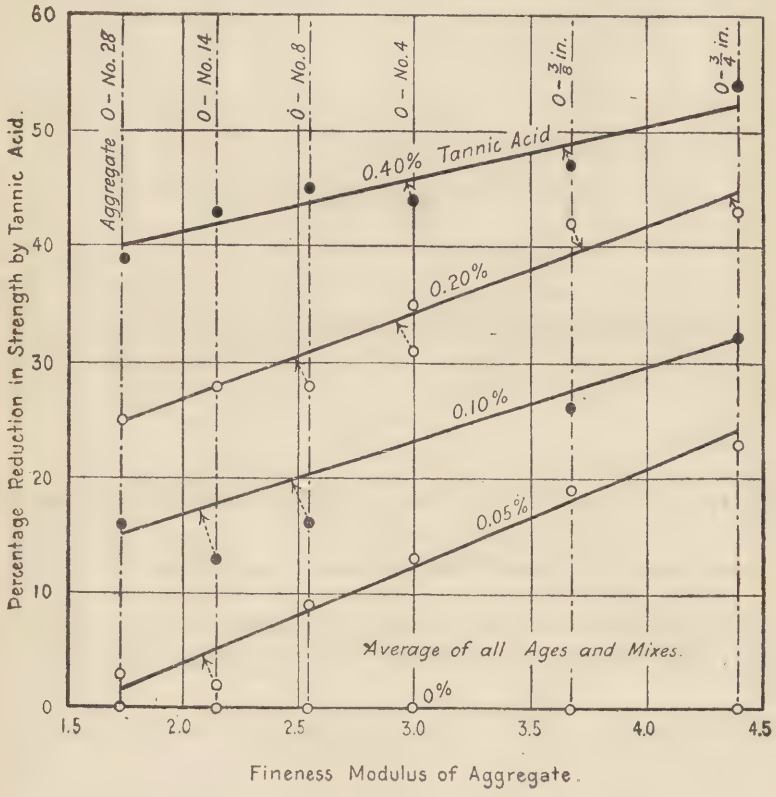


FIG. 11.—REDUCTION IN STRENGTH OF CONCRETE BY TANNIC ACID.

In general, the values are the average of 80 tests from 4 mixes and 5 ages. Compare Fig. 10.

The following equation represents the average values in Fig. 16, for the range of tests herein reported:

$$P = \frac{70}{2.1^t} + 30$$

where P = per cent of strength of concrete with clean aggregates
t = tannic acid (per cent of weight of mixing water, an exponent).

It was pointed out above that there is an intimate relation between the strength of the concrete and the water-ratio. The water-ratio may be varied by any one (or combinations) of the following methods:

1. Changing the mix.
2. Changing the grading of the aggregate.
3. Changing the consistency of the concrete.

In view of the well-defined water-ratio-strength relation let us see if the relation brought out by Fig. 16 is in agreement with the information in Tables 4, 5 and 6 and Fig. 5, 6, 10 and 11.

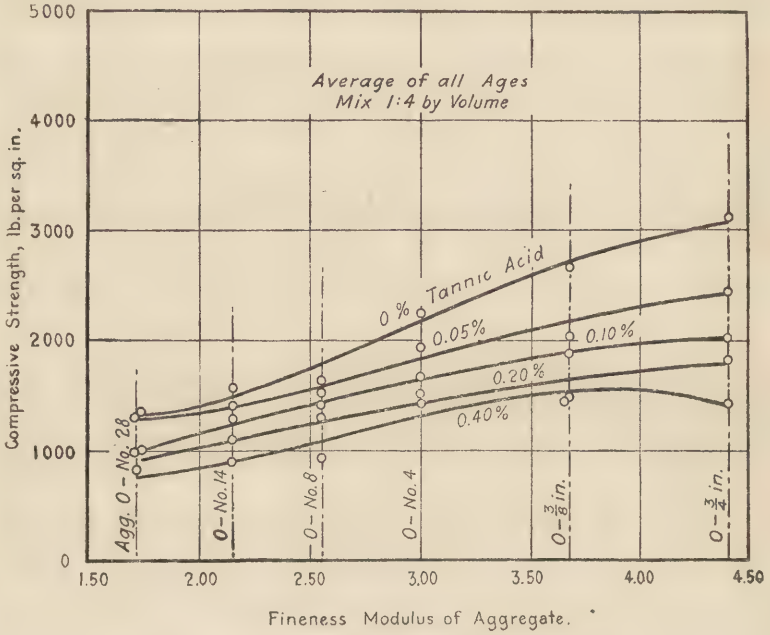


FIG. 12.—EFFECT OF SIZE OF AGGREGATE ON THE STRENGTH OF CONCRETE.

Mix 1: 4 by volume. In general, the values are the average of 20 tests from 5 ages. Similar curves may be drawn for 1: 2, 1: 3 and 1: 5 mixes.

Consider for example the 0 to ¾-in. aggregate coated with 0.40 per cent tannic acid. Assume this aggregate to be mixed in one-bag batches of concrete, using 1: 2 and 1: 5 mixes, respectively. It is obvious that the quantity of tannic acid in the batch of 1: 5 concrete is 2½ times that in the 1: 2 concrete. Reference to Tables 4 and 5 shows that the increase in water content in the 1: 5 concrete over the 1: 2 is only 61 per cent; therefore, the concentration of the tannic acid solution is less in the richer mixtures, and accordingly the reduction in strength of the concrete is less.

Fig. 10 and 11 and Table 6 show that, other factors being constant, concrete made from the finer aggregate is less affected than that made from the coarser aggregates. Reference to Tables 4 and 5 will show that concrete made from the finer aggregate contains more water and therefore, for a given mix, given consistency, and given percentage of tannic acid (in terms of the aggregate), the concentration of the tannic acid solution will be less and consequently the reduction in strength of the concrete less for the finer aggregate.

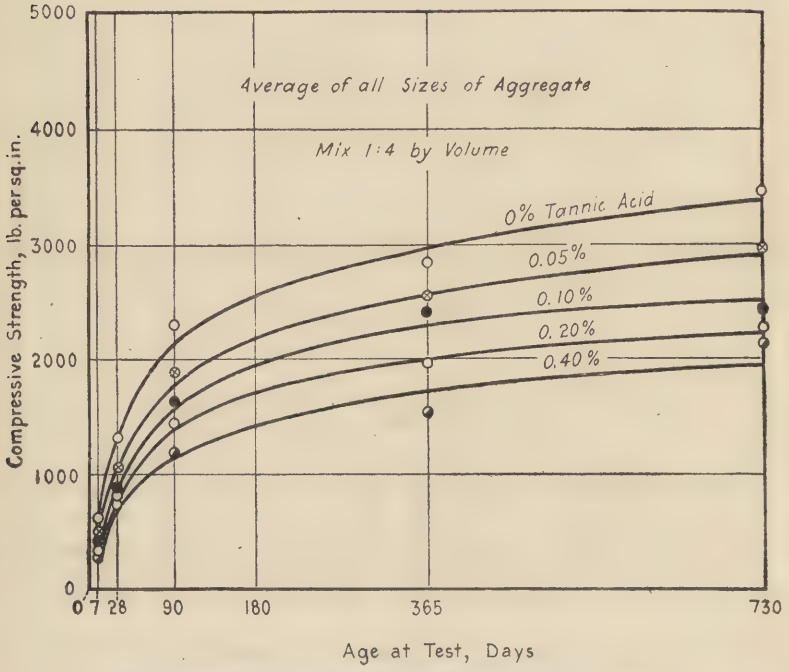


FIG. 13.—EFFECT OF AGE ON THE STRENGTH OF CONCRETE.

Mix 1: 4 by volume. In general, the values are the average of 24 tests from 6 sizes of aggregate. Similar curves may be drawn for the other mixes from data in Tables 4 and 5. Compare Fig. 14.

Effect of Consistency of Concrete.—In these series of tests the consistency of the concrete was not varied. However, the general relation brought out by Fig. 16 indicates that the wetter consistencies would be less affected than the drier ones, since the concentration of the tannic acid will become less as the consistency of the concrete is increased.

Age of Concrete.—The effect of age on the strength of concrete is shown in Fig. 13 to 15. The strength of the concrete increased with the

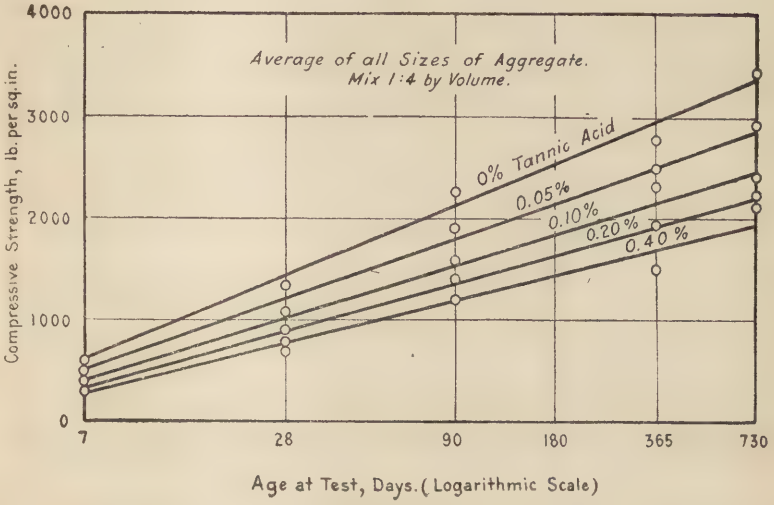


FIG. 14.—EFFECT OF AGE ON THE STRENGTH OF CONCRETE.

Mix 1: 4 by volume. Same data as in Fig. 13 with age platted to logarithmic scale. In general, the values are the average of 24 tests from 6 sizes of aggregate. Similar curves may be drawn for the other mixes from data in Tables 4 and 5.

TABLE 7.—WEIGHT OF CONCRETE.

Weights determined immediately after removal from form.
Each value is based on the weights of twenty 3 by 6-in. cylinders.
The presence of tannic acid had no appreciable influence on the weight of the concrete.

Size of Aggregate	Weight of Concrete, lb. per cu. ft.			
	Mix 1 : 2	Mix 1 : 3	Mix 1 : 4	Mix 1 : 5
0 to No. 28	134	133	129	127
0 to No. 14	137	135	132	131
0 to No. 8	139	137	135	133
0 to No. 4	143	141	140	139
0 to ⅜ in.	146	145	143	143
0 to ¾ in.	148	149	147	147

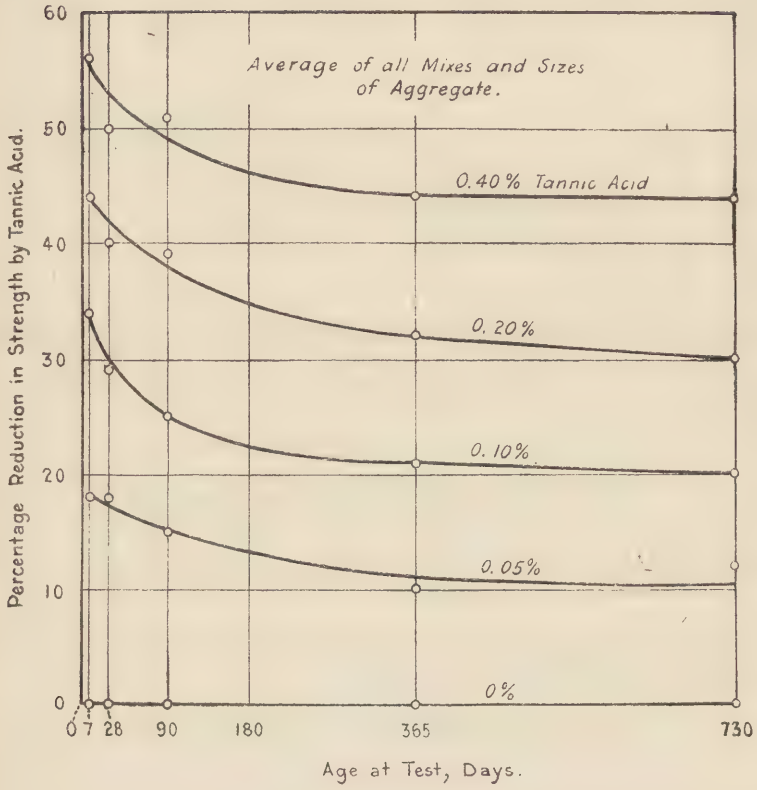


FIG. 15.—REDUCTION IN STRENGTH OF CONCRETE OF DIFFERENT AGES BY TANNIC ACID.

In general, the values are the average of 120 tests from 6 sizes of aggregate and 5 mixes. Compare Fig. 9.

age according to a definite law for all mixes, both with and without tannic acid. The curves in Fig. 14 (which are the same as Fig. 13, except for the age scale) show that there is a linear relation between the strength of concrete and the logarithm of its age up to 2 years, so long as the concrete is not allowed to dry out. Average strengths for 1:4 concrete without tannic acid (Fig. 13 and 14) were about as follows:

7 days	600	lb. per sq. in.
28 "	1400	" " " "
3 months	2100	" " " "
1 year	3000	" " " "
2 years	3400	" " " "

It should be borne in mind that the average aggregate was quite fine, consequently the above strengths are much lower than would have been secured with the usual concrete aggregates. Diagrams similar to Fig. 13 and 14 may be drawn for the other mixes from values in Tables 4 and 5.

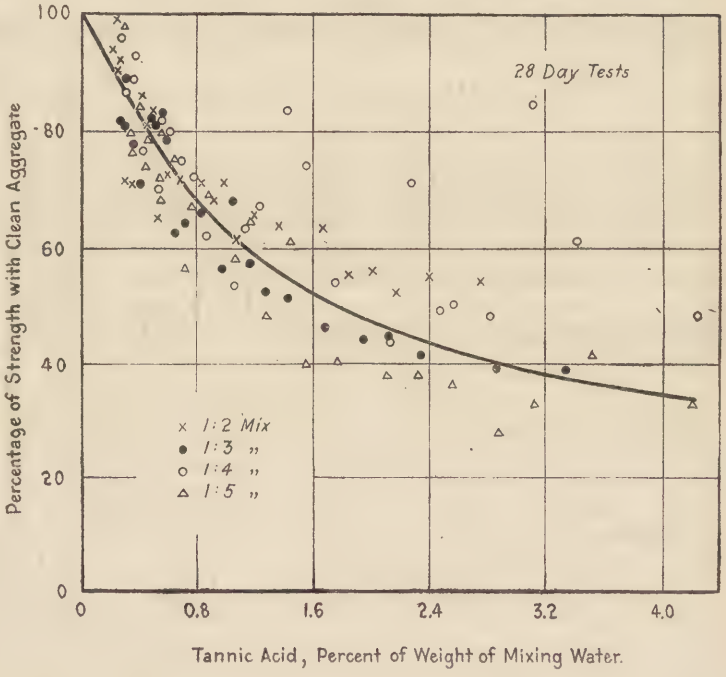


FIG. 16.—EFFECT OF TANNIC ACID ON THE STRENGTH OF CONCRETE.

The values are the average of 4 tests made on different days. Similar curves may be drawn from data in Table 6 for 7-day, 3-month, 1 and 2-year tests.

Concrete which has thoroughly dried out shows little or no further increase in strength, so long as it remains dry. The relation between age and strength of concrete shown by these tests have been brought out by many other groups of tests carried out in this and other laboratories.[1]

The values in Fig. 9 and 15 bring out the relative effect of the age of the concrete as it is influenced by the presence of tannic acid. In these figures all mixes and sizes of aggregate have been averaged. At 7 days the strength is reduced by about 33 per cent by 0.10 per cent tannic acid; for the same condition the strength is reduced about 30 per cent at 28 days and about 20 per cent at 1 and 2 years. For all mixes and sizes of aggregate, the strength is reduced to a greater extent at 7 and 28 days than at 1 and 2 years.

Surface Loam.—The tests and discussion show the importance of avoiding the use of sands containing organic impurities. Surface loam is a common source of organic material. Contrary to the conclusions based on numerous published tests, surface loam *always decreases* the strength of a *properly proportioned* concrete due to two distinct causes:

1. Presence of organic materials.
2. Additional water required to produce a concrete of a given plasticity.

A concrete in which the aggregate is too coarse for highest strength may be slightly improved by the addition of loam or other finely divided material. This means simply that the increase in strength due to a better grading of aggregates more than counter-balances the ill effects of the admixture.

Care should always be taken to remove the overburden of soil in sand and gravel pits. Washing when on a comprehensive scale is generally effective in removing loam. A superficial examination may not reveal the presence of organic impurities in sands. The colorimetric test described below is the only safe guide now known.

TEST FOR ORGANIC IMPURITIES IN SANDS.

Untried sands should always be tested for organic impurities before they are used in concrete. The "colorimetric" test has been found serviceable for this purpose. The test may be made in the field with little difficulty. The field test consist of shaking the sand thoroughly in a dilute solution of sodium hydroxide (NaOH) and observing the resultant color after the mixture has been allowed to stand for a few hours. Fill a 12-oz. graduated prescription bottle to the 4½-oz mark with the sand to be tested. Add a 3-per-cent solution of sodium hydroxide until the volume of the sand and solution, after shaking, amounts to 7 oz. Shake thoroughly and let stand for 24 hours. Observe the color of the clear liquid above

[1]See "Effect of Age on the Strength of Concrete," by Duff A. Abrams, *Proceedings*, Am. Soc. Testing Mat., Vol. XVIII, Part II (1918), and "Some Tests on Age and Strength of Concrete," by H. F. Gonnerman, *Proceedings*, American Concrete Institute (1918).

the sand. A good idea of the quality of the sand can be formed earlier than 24 hours, although this period is believed to give best results. If the solution resulting from this treatment is colorless, or has a light yellowish color, the sand may be considered satisfactory in so far as organic impurities are concerned. On the other hand, if a dark-colored solution is produced, the sand should not be used in high-grade concrete, or used only after mortar or concrete strength tests have shown it to be satisfactory for the purpose.

The 1919 report of Committee C-9 on Concrete and Concrete Aggregates of the American Society for Testing Materials contains a description of the above-mentioned test under the title "Abrams-Harder Field Test for Organic Impurities in Sands." A colored plate which accompanies that report will be of assistance in interpreting the results of the colorimetric test.[1]

[1] *Proceedings*, Am. Soc. Testing Mat., Vol. XIX, Part I, p. 321 (1919).

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Sugar added to both natural and portland cements gives increased strengths.

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Action of Sulphur Contained in Portland Cement and Slag Cement, by Gobrich;
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Tensile and Compressive Strength of Mortar Containing Waterproofing Compounds,
Tech. Paper 3, Bureau of Standards, 1912.

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Tensile tests on 1-3 mortar in which sand from ordinary gravel, apparently suitable for concrete work, gave low strengths. After washing sand, results were normal; examination of wash water showed presence of albuminoid N; experiments by Mass. Board of Health using 60 in 100,000 parts of H_2O lowered tensile strength of 1-3 mortar from 219 to 35 lb. in 7 days, and from 316 to 48 lb. in 28 days. E. E. Free claims that complex form of tannic acid surrounds each sand grain and prevents union of sand and cement.

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Two theories for prevention of reactions of compounds.

Possible Explanation of Defective Sands, by E. E. Free;
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Effect of Hydrated Lime and Other Powdered Admixtures in Concrete

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With an Appendix on
"Further Tests of Hydrated Lime in Concrete"

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FOREWORD

The paper on the "Effect of Hydrated Lime and Other Powdered Admixtures in Concrete" was originally published in the *Proceedings* of the American Society for Testing Materials, Part 2, 1920. Acknowledgment is made to the Society for permission to reprint the report in Bulletin form.

Most of the one, two and five-year tests in Tables 5, 8, 9, 14, 15 and 19 have been added since the original publication of this report by the A.S.T.M.

Since the original report was put into type we have made a supplemental investigation covering certain features not studied in the earlier tests. Compression tests of concrete were made on 1720 6 by 12-in. cylinders at the age of 28 days. The results of these tests were given in the Appendix, under the title, "Further Tests of Hydrated Lime in Concrete."

In the second edition of this Bulletin no changes have been made in the text. Tables 9 and 19 have been revised to include data of the five-year tests; Fig. 1, 2 and 4 have been revised to include two and five-year values, and Fig. 8 to include one-year values. Later references have been added in the bibliography.

EFFECT OF HYDRATED LIME AND OTHER POWDERED ADMIXTURES IN CONCRETE.[1]

By Duff A. Abrams.

Introduction.

There is a keen interest in engineering circles at the present time in the effect of powdered admixtures in portland cement concrete. Many types of inert admixtures have been used designedly or due to their presence in the aggregate. The use of sands containing silt and crushed stone containing dust are usual examples of powdered admixtures. The so-called sand-cements are only another phase of the same subject. The use of hydrated lime in quantities up to 5 or 10 per cent of the weight of the cement has gained considerable vogue due to the feeling that it improved the workability of concrete, or increased the strength and water-tightness. Published tests may be found which appear to support the above conclusions. However, it will be seen below that more thorough tests show the error of these statements with reference to the strength and workability of mixtures usually used for structural purposes. Published data on this subject are generally inconclusive and conflicting due to lack of scope in the tests, or to confining the investigations to briquet tests of sand mortars. Water-tightness was not studied in this investigation.

Studies of the effect of admixtures on the strength and other properties of concrete have been under way in this Laboratory for 4 years. This report is confined to powdered admixtures which are essentially inert in the presence of water and cement, as contrasted with liquids or soluble materials. While the major portion of the tests were made with hydrated lime, 17 other materials were also used, in order to determine the general effect of inert powdered admixtures.

The concrete materials were of commercial quality. Most of our studies were made on compression tests of 6 by 12-in.

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[1] Authorized reprint from the Proceedings of the American Society for Testing Materials, Vol. 20, Part 2, 1920. The discussions of this paper which appear in the Proceedings are omitted from this Bulletin.

concrete cylinders; some investigations included also tension and compression tests of mortar. An important feature was the wear tests of concrete made in the Talbot-Jones rattler. Bond tests were made in one series. Studies of evaporation and absorption were made on concrete containing hydrated lime and other admixtures.

The concrete was mixed by hand, each specimen being made from a single batch. The quantity of admixture was generally based on the volume of the cement in the batch and was an addition to rather than a replacement of the cement. Test pieces were stored in damp sand until the day of test, unless otherwise noted. The average values given in the tables and diagrams are generally based on 5 tests made on different days; in many instances 10 or 15 tests were made. The tests covered concretes of a wide range of mixes, consistencies, size and grading of aggregates, etc. Tests were made at ages of 3 days to 1½ years; specimens are on hand for test up to 5 years.

This report covers six different investigations, and includes about 20,000 tests. The work was done as a part of the experimental researches in the properties of concrete and concrete materials being carried out through the cooperation of Lewis Institute and the Portland Cement Association.

OUTLINE OF TESTS.

The six series of tests in which powdered admixtures were used, may be characterized as follows:

Series 58 and 59, Tests of Sand and Slag Cements;

Series 100, Effect of Consistency on the Strength of Cement Mortars;

Series 104, Effect of Hydrated Lime on the Bond and Compressive Strength of Concrete;

Series 114, Effect of Hydrated Lime on the Strength and Wear of Concrete;

Series 130, Effect of Powdered Admixtures on the Strength and Wear of Concrete.

Series 58 (1916).—Tension and compression tests of mortar and compression tests of concrete were made at ages ranging from 7 days to 1 year, using cements with which sand or granulated blast furnace slag, in quantities up to 50 per cent by weight were mixed prior to final grinding. This series included about 2000 tests; see Fig. 11.

Series 59 (1916).—Compression tests were made on 1320 2 by 4-in. cylinders of 1 : 3 mix at ages of 7 and 28 days, using sands of 9 different gradings and the same cements described under Series 58. See Fig. 12. It should be noted that these cements were different from those in the later investigations; in practically all the later tests the powders were *added* to the cement in the batch. In two of the minor series (100 and 104) the admixtures *replaced* cement at the time the concrete was mixed.

Series 100 (1917).—A special study was made of the effect of the consistency of mortars using different percentages of hydrated lime, kieselguhr, kaolin, powdered limestone and slag. In this series the admixtures replaced equal volumes of cement. The consistency varied from dry to very wet. Compression tests were made on 4550 2 by 4-in. cylinders at ages of 7 days, 28 days, 3 months, and 1 year; see Fig. 10.

Series 104 (1918).—Included parallel compression and bond tests of 1 : 5 concrete at ages of 7 days to 1 year. Hydrated lime was used as an admixture *replacing* cement up to 50 per cent of the volume of cement in the original mix. This series comprised 450 tests.

Series 114 (1918).—This was our first comprehensive investigation of the effect of hydrated lime on the strength of *concrete*. The hydrated lime was *added* to the batch up to 50 per cent by volume of cement. The consistency was varied from what we term "relative consistency" 0.90 to 2.00; the mix from 1 : 9 to 1 : 2 by volume; and the size of aggregate from 14-mesh sand to 1½-in. aggregate. Compression tests of 6 by 12-in. concrete cylinders were made at ages of 7 days, 28 days, 3 months, and 1, 2 and 5-years. In one group the curing condition of the concrete was varied in order to determine the effect of hydrated lime on the strength of concrete stored in damp sand for different periods followed by air storage. (See Table 9 and Fig. 9.) Wear and compression tests of concrete were carried out for 0, 10 and 33 per cent hydrated lime, using a 1 : 4 mix with 10 different aggregate gradings. (See Table 11.) This series includes 3420 6 by 12-in. cylinders and wear blocks.

Series 130 (1919-20).—In this investigation many of the features of Series 114 were repeated. Most of the tests were made with high calcium hydrated lime; in one group high magnesium lime and 17 other powdered materials were used. (See Tables 3, 13, 15.) The mix varied from 1 : 9 to 1 : 2; consistency from dry to very wet (relative consistency 0.90 to 2.00); size of aggregate from 28-mesh sand to 1½-inch graded aggregate. In general powdered admixtures were used in quantities up to 50 per cent of the volume of the cement.

Compression tests of 6 by 12-in. cylinders were made at ages of 3, 7 and 28 days, 3 months and 1 year. Wear tests were made on concrete blocks at age of 3 months, with mixtures ranging from 1 : 4½ to 1 : 2½, using hydrated lime up to 33 per cent. In this series, a special effort was made to study the effect of admixtures on the plasticity or workability of the concrete by means of the slump test. This series included about 7500 tests.

MATERIALS.

The concrete materials used in these investigations were of commercial quality. In general the cements were mixtures of equal parts of 4 or 5 brands of portland cement purchased in the Chicago market. In Series 58 and 59 sand and slag cements were prepared by grinding a portland cement with 10 to 50 per cent of the admixture (by weight) in a laboratory tube mill. In proportioning, all cements were assumed to weigh 94 lb. per cu. ft. Mortar strengths and miscellaneous tests of the cements are given in Table 1.

The aggregates consisted of sand and gravel from the Elgin, Ill., pit of the Chicago Gravel Company. This is a well-graded material with a preponderance of limestone particles.

In many of the tests the aggregates were separated into a number of sizes by the screens mentioned below and recombined in order to secure predetermined sieve analyses. The sieve analyses of one group of aggregates graded in such a way as to give a constant fineness modulus are given in Table 11.

Sieve analysis, unit weights and fineness moduli of the aggregates are given in Table 2. The fineness modulus is used as a measure of the size and grading of the aggregate; it is the sum of the percentages in the sieve analysis, divided by 100, using the following sizes from the W. S. Tyler Company's standard screen scale: 100, 48, 28, 14, 8, 4, ⅜ in., ¾ in., and 1½ in.[1]

The principal admixture used in this investigation was high calcium hydrated lime. In Series 130 high magnesium lime and 17 other admixtures were used. The miscellaneous admixtures were, in general, of about the same fineness as commercial portland cement. Many of them were ground in a laboratory tube mill.

The fineness, unit weight and normal consistency of the admixtures are given in Table 3. In the case of hydrated lime, kieselguhr, mica and a few other admixtures, it was impossible to determine the fineness by the ordinary sieving methods, hence values are not reported. Normal consistency was determined by the Vicat needle by the method used for portland cement.

The water used was from Lake Michigan.

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[1] For further details concerning the fineness modulus of aggregate, see "Design of Concrete Mixtures," *Bulletin 1*, Structural Materials Research Laboratory, Lewis Institute, Chicago.

TEST PIECES.

The size and number of test pieces in each series are indicated under Outline of Tests. All test pieces were made in metal forms. The concrete mixes are expressed as one part cement to a given number of volumes of aggregate mixed as used. For example a 1 : 5 mix indicates that 1 cu. ft. of cement is combined with 5 cu. ft. of mixed aggregate; this mixture is about equivalent to the ordinary 1 : 2 : 4. The actual quantities of materials for a batch were determined by weight. The quantity of concrete required for one specimen was proportioned and mixed separately. Mixing was done by hand with a bricklayer's trowel in a galvanized iron pan.

The consistency of the concrete is an important feature. The quality of water required by a unit volume of concrete will depend on the following factors:

1. The "workability" of the concrete.
2. The quantity of cement (the mix);
3. The normal consistency of the cement;
4. The size and grading of the aggregate;
5. The absorption of the aggregate;
6. The water contained in the aggregate;
7. The normal consistency of the admixtures;
8. The quantity of admixture.

In proportioning the quantity of water for a batch of concrete in experimental work where we are endeavoring to establish fundamental principles, it is necessary to take all these factors into account. The quantity of the water to be used in a given batch was calculated by a formula which had been derived from earlier tests.

For the tests in Series 130, the plastic condition of the concrete was determined by the "slump test." This test was made by placing the specimens in a 6 by 12-in. steel cylinder form* in the usual manner, by puddling in 3 layers with a ⅝-in. steel bar pointed at the lower end. Immediately after molding, the form was slipped off by a steady upward pull. The shortening of the cylinder measured in inches is the "slump." A relative consistency of 1.00 or normal consistency is such as will give a slump of about ½ to 1 in. Other "relative consistencies" require a pro-

* The present standard form for slump test is a truncated cone having a top diameter of 4 in. and bottom diameter of 8 in. and height of 12 in. See A.S.T.M. "Standard Method of Test for Consistency of Portland-Cement Concrete."

portional part of the quantity of water necessary for normal consistency. For example, a relative consistency of 1.10 requires 10 per cent more water than normal consistency.

In discussing the effect of water in concrete, the quantity of water is expressed in terms of the volume of cement; this is the water-ratio.

The concrete was placed in the 6 by 12-in. cylinder molds in layers of about 4 in.; each layer was puddled by means of a ⅝-in. round steel bar. The cylinders were capped when molded by means of neat cement paste and a piece of plate glass. The cylinders were removed from the forms on the day following molding, except for the 1 : 9 mix, which in some instances remained in the forms 2 days. In each series of investigations, one round of specimens was completed before the second round was begun. In this way each value is the average of 5 or more entirely independent tests, made on different days.

Wear tests were made on concrete blocks, 8 by 8 by 5 in. These blocks were molded in the same manner as indicated for the cylinders. The top surface was finished with a wood float and covered with building paper and damp sand until the forms were removed.

The bond-test pieces were made by imbedding 24-in. lengths of 1-in. plain round bars axially in 8 by 8-in. concrete cylinders.

All specimens were stored in damp sand until time of test, unless otherwise noted.

METHODS OF TESTING.

Mortar strength and miscellaneous tests of cement were made in accordance with the standard methods of the American Society for Testing Materials.

Compression tests of mortar cylinders were made in a 40,000-lb. Riehle testing machine. The 6 by 12-in. concrete cylinders were tested in a 200,000-lb. Olsen machine. A spherical bearing block was used on top of the cylinders.

Wear tests were made in the Talbot-Jones rattler, using blocks 8 in. square and 5 in. thick. The blocks were placed as shown in Fig. 14. The outside diameter of the ten-sided polygon thus formed is 36 in. During the test the front of the chamber was closed by means of a steel plate. The abrasive charge consisted of 200 lb. of cast-iron balls (10 of 3¾-in. and about 140

of 1⅞-in. diameter). These balls conform to the requirements for the standard rattler test of paving bricks of the American Society for Testing Materials.

The test consisted of exposing the inner faces of the concrete blocks to the wearing action of the charge for 1800 revolutions at the rate of 30 r.p.m. The machine was run for 900 revolutions in one direction, then reversed. The loss in weight during the test reduced to an equivalent depth was used as a measure of the wear.

Tests of bond between concrete and steel consisted of pullout tests of 1-in. plain round steel bars imbedded 8 in. in an 8-in. concrete cylinder. Slip-of-bar measurements were made during the test. The method of conducting the tests was similar to that used by the writer at the Universtiy of Illinois.[1]

Evaporation and absorption tests were made by weighing the blocks used in the wear tests.

TEST DATA.

Practically all of the test data from the six investigations of powdered admixtures mentioned above are given in the attached tables and diagrams. Most consideration has been given to the results of tests in Series 114 and 130; in making these tests we had the benefit of the data and experience gained in earlier work. The principal results of tests in each of Series 58, 59 and 100, are presented by a single diagram; see Fig. 10, 11 and 12. The tests in Series 104 are given in Table 10.

The values given in the tables and diagrams are in general the average of five or more tests. In the discussion all values are given equal weight whether based on 5, 10 or 15 tests. In many instances the results of tests of concrete containing powdered admixtures have been reduced to (*a*) percentages of the strength of similar concrete without admixtures; (*b*) per cent change in strength due to the presence of admixtures. These methods are helpful in showing the effect at a glance.

DISCUSSION OF TESTS.

Due to the large number of tests covered by this report the discussion will necessarily be confined to the most important

[1] See "Tests of Bond between Concrete and Steel," *Bulletin 71*, University of Illinois Eng. Exp. Station.

topics. For many other features the reader must refer to the accompanying tables and diagrams. An excellent check on the uniformity of the tests is found in the concordance of the data as shown by the regularity of the points on the curves, and from the fact that tests made in different series at intervals of several months give essentially the same results. The word *concrete* is here used in its general sense to include what are usually referred to as *mortar* mixes.

The general effect of admixtures is to reduce the strength of concrete in proportion to the quantity of admixture used. Some exceptions to this general conclusion are mentioned below.

EFFECT OF HYDRATED LIME AS AN ADMIXTURE IN CONCRETE.

The principal tests with hydrated lime are given in Tables 4 to 12; the change in strength is shown in Tables 17 to 19. It is impracticable in all cases to discuss separately the effects due to different causes, owing to the fact that in many instances two or more factors, such as mix, consistency, size of aggregate, age, etc., were varied simultaneously. Unless otherwise noted, the quantity of hydrated lime is expressed in terms of the volume of cement and was *added* to the cement. If it is desired to deal with weights, the necessary data will be found in Table 3.

Concrete of Different Consistencies.—The effect of hydrated lime, using concrete of different consistencies is shown in Table 4. The consistencies ranged from relative consistency 0.90 (dry) to 2.00 (very wet), the mix from 1 : 9 to 1 : 2. Tests were made at 28 days in Series 130. Similar tests for 1 : 4 mix only were made in Series 114, at ages of 7 days to 1 year. See Fig. 1.

The strength of the concrete, both with and without hydrated lime, was reduced by the addition of water. The maximum strength was found for relative consistency of 0.90. The strength of the concrete was reduced by hydrated lime for all consistencies and ages. The percentage reduction in strength for different consistencies is shown in Tables 18 and 19. These values were calculated from the slopes of the curves in Fig. 1 and 3. It will be noted that in these figures the relation between the strength and volume of hydrated lime used is essentially a linear one. The wetter consistencies are more affected by the presence of hydrated lime than the drier ones. In Series 130, in the case of the 1 : 4 mix, representing concrete of the quality used in road construc-

tion, the reduction in strength at 28 days for relative consistency 1.00, is 0.48 per cent for each 1 per cent of hydrated lime; for relative consistency 2.00, this value is increased to 0.62 per cent. In Series 114 the corresponding values are 0.66 and 0.74.

Water Constant.—Table 12 gives the results of a series of tests in which hydrated lime up to 50 per cent of the volume of the cement was used in mixes of 1 : 5, 1 : 4 and 1 : 3 proportion. The concrete was mixed with a quantity of water which gave a normal consistency with 50 per cent of hydrated lime; other batches were mixed with the same quantity of water. This gave a graduated series of consistencies, the mix without hydrated lime being considerably wetter than the others. These tests show that with the water constant, the strength of concrete is practically uniform.

Water-Ratio-Strength Relation.—The water-ratio is defined as the ratio of the volume of water to volume of cement in the batch, considering 94 lb. of cement as 1 cu. ft. Many previous investigations have shown that there is a fixed relation between the water-ratio and the strength of concrete, regardless of the reason for the use of a particular quantity of water, so long as the concrete is plastic and the aggregate is not too coarse for the quantity of cement used. The water-ratio-strength relation is platted in Fig. 7 for certain 28-day tests without hydrated lime and with 50 per cent hydrated lime. Similar curves may be drawn for other percentages. In computing the water-ratio, all water except that absorbed by the aggregate, was accredited to the cement; that is, the water absorbed by the hydrated lime was not deducted. These curves show that the water-ratio-strength relation holds with and without hydrated lime, although the relation is not the same. It was found impracticable to determine the absorption of hydrated lime, although it is probable that if correction could be made for this factor, the water-ratio-strength relation would be found to hold for concrete containing admixtures in the same manner as has been found for those without admixtures. The water-ratio of 1 : 4 mix, relative consistency 1.10, with aggregate of fineness modulus 5.75, without hydrated lime is 0.78; with 50 per cent hydrated lime it is 1.00. The strength in the first instance is 3100 lb. per sq. in., while with the 50 per cent hydrated lime it is 2400 lb. per sq. in. These curves bring out the water-ratio-strength relation for given conditions

but do not show directly the effect of hydrated lime on the strength of concrete.

The water-ratio-strength relation for tests in Series 100 is shown in Fig. 10.

Mix.—The effect of hydrated lime on the strength of concrete of different mixes is shown in Tables 4 to 7, 12 and 14, and Fig. 2 to 5. The change in strength of concrete of different mixes, due to hydrated lime, is shown in Tables 18 and 19. In general the strength of concrete was reduced by hydrated lime for all mixes. The leaner mixes are, however, reduced only to a slight extent and the 1 : 9 mix (about the same as the usual 1 : 3½ : 7 mix) gave a slight increase in strength with hydrated lime. This slight increase in strength of the lean mixes was probably due to the fact that the aggregate was graded too coarse for the quantity of cement; in other words, the admixture slightly improved the *grading* by supplying fine material.

For the ordinary range of mixes and consistencies (1 : 5 to 1 : 4, and relative consistency 1.00 to 1.25), the strength of the concrete was reduced 0.50 per cent for each 1 per cent of hydrated lime, in terms of volume of cement.

In arriving at this value, richer and leaner mixtures and wetter and drier mixtures than those indicated were not considered. The following were also excluded on account of not being in the category of *usual* concrete mixtures:

(*a*) Concrete of aggregates smaller than ¾-in.

(*b*) Aggregates graded to 1½ in., but coarser or finer than is good practice (fineness modulus lower than 5.50 or higher than 6.00 in Table 6).

(*c*) Tests in Table 10 in which cement was replaced by hydrated lime.

(*d*) Tests in Table 11 in which a constant quantity of mixing water was used.

Size and Grading of Aggregate.—A distinction is made between *size* and *grading* of aggregate. The size refers to changes in the maximum size with a given type of sieve analysis; grading refers to the type of the sieve analysis curve for a given maximum size. The fineness modulus of the aggregate is used as a measure of the size and grading. Low values of fineness modulus correspond to finer aggregates; higher values to coarser.

The results of tests from Series 114 and 130 on 1 : 5 and

1 : 4 mixes are given in Table 7. The aggregate ranged in size from 28-mesh sand up to 1½-in. graded aggregate. The percentage change in strength, due to the presence of hydrated lime is given in Table 17. The finer sands showed a slight increase in strength while the aggregate graded above ⅜ in. in size showed a decrease in strength with the addition of hydrated lime.

One group of tests was made with aggregates of different gradings in mixes 1 : 9 to 1 : 2; see Table 6 and Fig. 5. The different values of fineness modulus were secured by mixing well-graded sand and pebbles (up to 1½ in.) in varying proportions. For the low values of fineness modulus a large percentage of sand was used; for high values the percentage was small. The sand had a fineness modulus of 3.0 and the coarse aggregate a fineness modulus of 7.0; hence, by mixing these materials in different proportions, any value between these limits can be secured. For the usual mixes with aggregates graded up to 1½ in. values of fineness modulus of 5.5 to 6.0 give best results. The change in strength, due to hydrated lime will be found in Table 18. For the usual grading and mixes, hydrated lime gave the same reduction in strength noted above from another group of tests; that is, 0.50 per cent for each 1 per cent of hydrated lime. In the finer gradings (low fineness modulus) the strength showed less reduction and for leaner mixtures a slight increase in strength with hydrated lime. A similar relation was found for the very coarse aggregates (fineness modulus 6.50 and 6.75). These results should be compared with those found for fine sands and lean mixes discussed above.

These tests bring out the fact that tests on sand mortars are not a safe guide as to what happens in concrete, since the compression tests of sand mixtures gave a slight increase in strength with the addition of hydrated lime, while the usual concrete mixes show a material reduction in strength.

In Table 11, ten different gradings of aggregate were made up in such a manner as to give a uniform fineness modulus of 6.04, using a 1 : 4 mix at 28 days. Hydrated lime was used in percentages 0, 10, and 33. The mean variation of the tests from the average is 4.2 per cent, indicating a practically uniform strength regardless of the widest variation in the grading of the aggregate. The tests with and without hydrated lime showed the same relation so far as grading of aggregate is concerned. How-

ever, the strength was reduced in all cases due to the presence of hydrated lime. The reduction in strength was 0.50 per cent for each 1 per cent hydrated lime.

High Magnesium versus High Calcium Hydrated Lime.—Most of the tests were made with high calcium lime; in Series 130 high magnesium hydrated lime was also used. Compression tests of 1 : 4 concrete were made at ages of 3 days to 1 year. Both types of hydrated lime gave the same results; the values in many instances were almost identical; see Tables 14 and 19.

Curing Condition.—The effect of hydrated lime on the strength of concrete cured under different conditions is shown in Table 9 and Fig. 9. Tests were made on a 1 : 4 mix, using 0, 10 and 33 per cent hydrated lime. Specimens were stored in damp sand for periods ranging from 1 day to 1 year, after which they were stored in air until tested at ages ranging from 7 days to 18 months. The actual strengths were also reduced to percentages of the strength of the concrete stored in damp sand through the entire curing period. If the presence of hydrated lime had a beneficial influence on the strength of concrete stored in air subsequent to the period stored in damp sand, the curves in Fig. 9 should show an upward trend. In general these curves are practically horizontal or show only a slight upward trend, indicating that hydrated lime was of no material benefit in raising the relative strength; while the actual strength was in general reduced by hydrated lime. In this group of tests care must be taken to distinguish between the *curing period* and the *age at test.* The discussion below on the evaporation and absorption also throws interesting light on this phase of the effect of hydrated lime in concrete.

Evaporation and Absorption.—In order to determine the effect of hydrated lime and other admixtures on the evaporation and absorption of water, careful weights were made on the wear blocks in Series 130. The results of wear tests are given in Tables 20 and 21.

The results of evaporation and absorption tests are given in Fig. 13. The evaporation was determined by weighing the blocks upon removal from damp sand at the age of 14 days and at intervals up to the time they were tested at the age of 3 months. The tests show that all the admixtures gave essentially the same results; that evaporation occurred more rapidly in the leaner mixes

than in the richer ones, and that the evaporation was slightly more rapid with hydrated lime than without, although there was little difference for quantities of hydrated lime less than 10 per cent. The blocks gained slightly in weight during the storage in damp sand. After storage for 10 weeks in air they showed a loss in weight of about 2½ per cent—equivalent to 25 to 30 per cent of the original mixing water.

Bond Tests.—Tests of bond between concrete and steel were carried out in Series 104. The results of parallel bond and compression tests on a 1 : 5 mix, using hydrated lime up to 50 per cent, are given in Table 10. It should be noted that in this series the hydrated lime *replaced* an equal volume of cement; consequently the quantity of cement decreased as the percentage of hydrated lime increased. This arrangement, of course, gave a much greater reduction in strength due to hydrated lime than was found in the tests in which the hydrated lime was added to a constant volume of cement. The bond resistance was affected in the same manner by the addition of hydrated lime as the compressive strength.

Density and Yield.—The density and yield of concrete were determined for all conditions. It is impracticable to give all of the results of these tests. However, the general trend of the values may be seen from Tables 22 and 23.

The density was calculated from the dimensions of the specimens, the volumes of materials used in the batch and the unit weight of the concrete. The density may be defined as the ratio of the total volume of solids in the mass to the volume of concrete. It will be noted that the maximum density was produced by the leaner mixes. As the proportion of cement increased the density was reduced. The density was also materially reduced by increasing the water content. Density was slightly reduced by the addition of hydrated lime; the addition of 50 per cent of hydrated lime to a 1 : 4 mix, consistency 1.10, reduced the density about 4 per cent.

The yield expresses the volume of finished concrete in terms of the volume of mixed aggregate as used.

The yield of concrete increased with the addition of powdered materials. The richer mixes were more affected than the leaner ones. For mixtures richer than 1 : 6, hydrated lime increased the

volume of concrete 50 to 60 per cent of the volume of loose lime added. For other materials the increase in volume (yield) appears to be proportional to the total volume of solid material in the admixture.

Plasticity of Concrete.—In Series 130 the plasticity of the concrete was measured by means of the slump test described above. A high value of slump indicates a more plastic concrete than a low one. Table 16 gives the results of one group of tests in which the mix and consistency were varied. The slump was only slightly affected by the presence of hydrated lime up to 50 per cent in the usual concrete mixtures. In the leaner mixes the slump was in general increased by the addition of hydrated lime. For the richer mixes the slump was decreased.

Addition versus Replacement.—Fig. 6 gives the relative strength of concrete for different mixtures and percentages of lime. This figure is based on tests in which hydrated lime was added to the cement. The curves in the upper right corner illustrate the method of calculating the effect of replacing cement by hydrated lime. In general the reduction in strength caused by replacing cement by hydrated lime was about 1¾ times that caused by adding hydrated lime to cement.

MISCELLANEOUS POWDERED ADMIXTURES IN CONCRETE

In addition to hydrated lime, compression tests of concrete were made on 17 different powdered admixtures; see Table 3. The results of compression tests are given in Tables 12 to 14. Wear tests were also made with a portion of these admixtures; see Tables 20 and 21. For compression tests of mortars of miscellaneous admixtures made in Series 100; see Fig. 10.

In studying the effect of admixtures, curves were platted showing the relation between the strength of concrete and percentage of material added; see Fig. 1 to 5. In general these curves are essentially straight lines, consequently the slope represents the rate of change of strength with the percentages of admixtures. Most of these admixtures gave essentially the same results and showed the same effect as hydrated lime. Usual concrete mixtures were reduced in strength. The only exception to this statement is pulverized blast furnace slag. Gypsum gave a much greater reduction in strength than any of the other materials.

Brick.—Common building brick from the Chicago district, crushed and pulverized, was used. The tests showed that the strength of 1 : 4 concrete at 28 days was reduced 0.08 per cent for each 1 per cent addition of powdered brick in terms of the volume of cement.

Clay.—The clay used was a light fluffy material from South Amboy, N. J. The strength of concrete was reduced 0.22 per cent for each 1 per cent of this material.

Fluorspar.—The fluorspar was obtained from a mine at Shawneetown, Ill. Concrete strength was reduced 0.43 per cent.

Gypsum.—A first-settle gypsum without retarder was used. The strength was slightly increased by 1 or 2 per cent of gypsum at ages of 3 and 7 days. The reduction in strength was very pronounced for quantities higher than 5 per cent at all ages. The average reduction was about 4 per cent for each 1 per cent of gypsum.

Hydrated Lime.—Under the same conditions as used in tests of other admixtures, hydrated lime showed a reduction in strength of 0.56 per cent. In using 0.50 per cent in the foregoing discussion a large number of tests from different series using different mixes, consistencies and ages were averaged.

Ironite.—Ground cast iron weighing 186 lb. per cu. ft., considerably coarser than other admixtures (residue of 45 per cent on 100-mesh sieve), used in quantities up to 10 per cent only, reduced the strength of concrete 0.16 per cent.

Kaolin.—Kaolin reduced the strength 0.41 per cent.

Kieselguhr.—Kieselguhr, from a California deposit, was the lightest of the admixtures used (weight, 13 lb. per cu. ft.). The strength of concrete was reduced 0.48 per cent.

Lava.—Ground lava rock from Twin Falls, Idaho, reduced the strength of concrete 0.40 per cent.

Limestone.—Pulverized limestone from the Chicago district, ground to a residue of 10 per cent on a 200-mesh sieve reduced the strength 0.39 per cent for each 1 per cent of limestone.

Mica.—The material used was a white flake mica ground in a laboratory tube mill. At earlier ages the strength of the concrete was slightly increased with the smaller percentages of mica. At 28 days and later periods the strength was reduced about 1.1 per cent for each 1 per cent admixture. These tests do not bear out the conclusions based on published reports which show a

very great reduction in mortar strength due to mica. Other tests are now under way in which a number of micaceous sands will be used.

Natural Cement.—Natural cement purchased in the Chicago market, was used in both compression and wear tests. (See Tables 8, 14 and 20.) These tests included mixtures from straight portland to straight natural cements. While natural cement gave a considerable strength when used alone, it is interesting to note that when mixed with portland cement it caused a reduction in strength for all percentages and for all consistencies and ages of concrete and gave results comparable in every way with other admixtures. Under the conditions mentioned above, the strength of concrete was reduced 0.38 per cent for each 1 per cent added.

Pitch.—Pitch was pulverized to a very fine powder; the fineness could not be determined by ordinary sieving methods. So far as the writer is aware, no one has advocated the use of this material in concrete; it was included in this investigation in order to study the effect of a powder of unusual origin on the strength of concrete. The strength was reduced 1.5 per cent for each 1 per cent of pitch.

Sand.—Clean silica drift sand from the Chicago district, ground to the fineness of portland cement, reduced the strength of concrete 0.37 per cent for each 1 per cent sand.

Slag.—Granulated blast furnace slag ground in the laboratory to the fineness of portland cement. The results of tests with slag differed essentially from all other admixtures in that the strength of concrete was slightly *increased* for all quantities up to 50 per cent of the volume of the cement which was the highest value used. This statement applies to mixes from 1 : 9 to 1 : 4, for different consistencies and ages. The 1 : 3 mix showed a slight loss in strength with the addition of slag. For the conditions discussed for other admixtures the slag increased the strength 0.12 per cent for each 1 per cent added. A similar relation has been pointed out by other writers both in this country and Europe. This result has been explained as due to chemical reactions between the slag and certain compounds in the cement. The principal constituents of this slag were: SiO_2, 34.8 per cent; CaO, 42.6 per cent; Al_2O_3, 15.0 per cent; Fe_2O_3, 3.7 per cent.

Tufa.—Tufa, a light, loosely-formed natural rock from Mount Angel, Ore., ground with difficulty, reduced the strength of concrete 0.51 per cent.

Whiting.—Commercial grade of whiting, reduced the strength of concrete 0.24 per cent.

Yellow Ochre.—Yellow ochre from Cartersville, Ga., reduced the strength of concrete 0.68 per cent.

EFFECT OF ADMIXTURES ON THE WEAR OF CONCRETE.

Three different groups of wear tests were carried out; see Tables 11, 20 and 21. All wear tests were made in the Talbot-Jones rattler, using 8 by 8 by 5-in. concrete blocks. The wear blocks were tested at 3 months after 14 days in damp sand, followed by air storage. Wear tests were made with admixtures of hydrated lime, kieselguhr, powdered limestone, slag, sand, and natural cement. This test was of such severity as to produce a wear of 0.4 to 0.5 in.

Slag showed the best results since the wear was no greater with 33 per cent slag than with straight cement; sand gave nearly as good results as slag; the other admixtures may be placed in the following order of merit; hydrated lime, natural cement, limestone and kieselguhr. There seems to be little reason for using these materials in concrete roads and other concrete subjected to wear; it is of interest to know that some of them do little or no harm. The principal danger from the use of admixtures in road concrete is that any excess of mixing water will cause the fine material to be floated to the surface and thus give concrete of inferior wearing resistance. The same statement applies to silt in sands and to crusher dust. Silt may contain organic impurities which materially reduce the strength of concrete.[1]

SAND AND SLAG CEMENTS.[2]

Two of the earlier investigations included tension and compression tests of mortar and concrete using sand and slag cements. In the preparation of these materials, the sand or slag was added to the cement before final grinding. The tests are summarized in Fig. 11 and 12. Mortar and miscellaneous tests are given in

[1] See "Effect of Tannic Acid on the Strength of Concrete," by Duff A. Abrams, Appendix 2, Report of Committee C-9 on Concrete and Concrete Aggregates, *Proceedings* Am. Soc. Testing Materials, Vol. 20, Part 1, p. 309 (1920). [Reprinted as Bulletin 7 Structural Materials Research Laboratory.]

[2] The term "slag cement" is used in this paper to designate a mixture of portland cement with various percentages of pulverized granulated blast furnace slag. The slag may be simply mixed or ground with the cement; in our case it was mixed. Care should be taken to distinguish between our usage and the same term applied to a product resulting from grinding slag with hydrated lime. Our use of "slag cement" is cognate with "sand cement."

Table 1. The slag cements showed more favorable results in all cases than the sand cements; slag up to 10 per cent produced no appreciable reduction in strength of 1 : 2 : 4 concrete; for 50 per cent slag the concrete strength was reduced to 65 per cent of the strength with cement only. Mortar strengths were less affected than the concrete; the lean briquets showed a strength with 50 per cent slag of about 95 per cent of cement only. It will be seen that the concrete tests do not bear out the indications of the briquet tests. The compression tests of 1 : 2 mortar, Fig. 11, show essentially the same result as the concrete.

Sand cements give less favorable results than the slag cements. In comparing these tests with the results from other admixtures it should be borne in mind that here cement was replaced by sand or slag. In general the effects of admixtures *ground* with cement are similar to those found with same materials simply mixed. Of course, some consideration must be given to the effect of the finer grinding of the cement in increasing the strength of the concrete.[1] It was impracticable to determine how much the fineness of the cement was changed by the addition of different percentages of sand or slag.

General Discussion.

The following discussions of a general nature have no direct bearing on the effect of admixtures:

Effect of Quantity of Cement.—The wide variation in the mixes used in these tests furnish information on the effect of variations in the quantity of cement. Fig. 8 gives a typical curve for 28-day tests. For the usual mixes (1 : 5 to 1 : 4) the strength increased 1 per cent for each per cent addition of cement. The same value was found in our tests on "Effect of Fineness of Cement" referred to above.

Consistency of Concrete.—A typical strength-relative consistency curve is shown in Fig. 8 for 1 : 4 concrete; similar curves may be drawn for other mixes and conditions from data given in the tables. The quantity of water in terms of the water-ratio is given in many of the tables.

Fineness Modulus of Aggregate.—A typical fineness modulus strength curve is given in Fig. 8 for 1 : 4 mix. The circles and

[1] See "Effect of Fineness of Cement," by Duff A. Abrams, *Proceedings* Am. Soc. Testing Materials, Vol. 19, Part 2, p. 328 (1919).

crosses refer to tests made in different groups giving fineness modulus values derived in different ways; see Tables 6 and 7. This curve shows the same relation that has been found in many other investigations carried out in this Laboratory; see *Bulletin* 1, previously referred to.

Effect of Age of Concrete.—All tests included in this report show that the strength of concrete increased with age so long as the concrete does not dry out. Fig. 8 shows a typical age-strength relation for concrete stored in a damp place. Table 9 shows that after concrete dries out (upon exposure to air for 2 to 4 weeks) there is little or no further increase in strength.

Curing Condition of Concrete.—Table 9 shows the importance of curing concrete under favorable conditions.

CONCLUSIONS.

The principal conclusions from these investigations are as follows:

1. In general the addition of powdered materials reduced the strength of concrete approximately in proportion to the quantity of admixture. Some exceptions are noted below.

2. In usual concrete mixtures, each 1 per cent of hydrated lime (in terms of the *volume* of cement) reduced the compressive strength 0.5 per cent; 1 per cent by *weight* of cement reduced the strength 1.2 per cent. The reduction in strength caused by *replacing* cement with an equal volume of hydrated lime was about 1¾ times that caused by adding hydrated lime.

3. High calcium and high magnesium limes produced the same effect.

4. The addition of 1 per cent of the following powdered admixtures in terms of the volume of cement *reduced* the strength of 1 : 4 concrete at 28 days by the following percentages: Brick, 0.08; clay, 0.22; whiting, 0.24; sand, 0.37; natural cement, 0.38; limestone, 0.39; lava, 0.40; fluorspar, 0.43; kaolin, 0.47; kieselguhr, 0.48; tufa, 0.51; hydrated lime, 0.56; ironite, 0.60; yellow ochre, 0.68; mica, 1.10; pitch, 1.50; gypsum, 4.00. For the same conditions the addition of 1 per cent of cement *increased* the strength of concrete about 1 per cent.

5. Pulverized slag up to 50 per cent of volume of cement gave a slight increase in strength of concrete (about 0.12 on the basis used above).

6. Rich concrete mixes showed a greater loss in strength due to powdered admixtures than the leaner ones. Lean mixes (1 : 9 to 1 : 6) and in those with aggregates graded too coarse for the quantity of cement used, the strength was little affected or was slightly increased by admixtures up to 50 per cent.

7. The wetter mixes showed a greater loss in strength than the dry, due to the addition of hydrated lime.

8. The effect of admixtures was in general independent of the age of the concrete.

9. Sand and slag cements gave results comparable to those from powdered materials simply mixed in the concrete.

10. Hydrated lime and other powdered admixtures used in these tests slightly increased the workability of the leaner mixes (1 : 9 and 1 : 6) as measured by the slump test. Ordinary mixes (1 : 5 and 1 : 4) were little affected; richer mixes (1 : 3 and 1 : 2) were made less plastic.

11. The wear of concrete was not sensibly increased by hydrated lime or other admixtures up to 20 per cent of the volume of cement.

12. The bond resistance was affected in the same manner as the strength by the presence of hydrated lime.

13. Hydrated lime had little effect on the absorption of dry concrete, increased the evaporation of water from wet concrete and produced no beneficial effect on the strength of concrete stored in air.

14. Powdered admixtures increased the yield of concrete. For hydrated lime in the usual concrete mixtures the increase in volume of the concrete (yield) was about 60 per cent of the loose volume of lime added.

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APPENDIX.

FURTHER TESTS OF HYDRATED LIME IN CONCRETE.

By Duff A. Abrams.

Introduction.

The tests in this Appendix are supplemental to the foregoing report on the "Effect of Hydrated Lime and Other Powdered Admixtures in Concrete." The tests were outlined subsequent to the publication of the original paper, for the purpose of securing data on certain features not studied in the earlier tests.

Compression tests of concrete were carried out at the age of 28 days with the following objects in view:

1. To determine the nature of the relation between the quantity of hydrated lime and the strength of concrete for small percentages of lime;

2. To study the effect of the addition of small quantities of Portland cement in same manner as hydrated lime;

3. To secure additional data on the effect of hydrated lime up to 33 per cent of the volume of cement in the batch;

4. To repeat certain tests in earlier series in which concrete of a wide range of mixtures and consistencies was used;

5. To make further studies of the effect of hydrated lime on the workability or plasticity of concrete;

6. To compare pebbles and crushed limestone as coarse aggregates in concrete in which hydrated lime was used;

7. To secure average values of greater accuracy by making 10 tests instead of 5 as in earlier investigations.

All tests were made at 28 days; the effect of hydrated lime on concrete tested at ages ranging from 7 days to 2 years is covered in earlier series. In order to avoid confusion the numbering of tables and figures has been continued from the original paper.

OUTLINE OF TESTS.

This investigation included compression tests of 1720 6 by 12-in. concrete cylinders. A skeleton outline of the tests is given in Table 24. For convenience of reference and discussion the tests were divided into groups. All mixtures are expressed as one volume of cement to a given number of volumes of mixed aggregate as used. One specimen of each kind was made before beginning a second round; this process was continued until 10 specimens in each set were made. It will be seen that in this way each value in the tables is the average of 10 independent tests.

Group 1.—Concrete of mixtures ranging from 1 : 6 to 1 : 2 and relative consistencies 0.90 to 1.50 (consistencies from dry to "sloppy") were mixed with hydrated lime in quantities 0, 5, 10, 20 and 33 per cent of the volume of cement. This group of tests repeated a part of Series 114 (1918) and Series 130 (1919-20); compare Table 4 and Fig. 2 of original report.

Group 2.—Mix 1 : 4, relative consistency 1.10. Both pebbles and crushed limestone were used as coarse aggregate. Two different aggregate gradings were used throughout with the same percentages of hydrated lime as in Group 1.

Group 3.—1 : 5 and 1 : 4 mixes, both hydrated lime and portland cement were used as "admixtures." Tests were made with 1 and 2 per cent of admixture in addition to the higher percentages used in Groups 1 and 2. This group differed from the others in that the same *quantity* of mixing water was used throughout for a given mix. The quantity of water for each specimen was fixed at an amount that would give a plastic concrete for the highest percentage of admixture, consequently the concrete became progressively drier and drier as hydrated lime or cement was added.

Group 4.—1 : 4 mix; differed from Group 3 in that the concrete was mixed as nearly as practicable to the *same workability or plasticity*. The "flow" of the concrete was used as a measure of workability. The attempt was made to secure the same flow for all percentages of admixtures; this required an increase in the quantity of mixing water as hydrated lime or cement was added.

MATERIALS, TEST PIECES, AND METHODS OF TESTING.

In general, materials and test methods were similar to those used in the earlier tests. The cement consisted of a mixture of equal parts of 5 brands of portland cement purchased in Chicago. Two lots of cement were used: Lot No. 4951 in the first 5 rounds, and Lot No. 5075 in the last 5 rounds of concrete tests. The results of standard tests on the cement are given in Table 25. The two lots of cement were tested at different times.

The fine aggregate for concrete was a well-graded sand from the Elgin, Ill., pit of the Chicago Gravel Co. Two types of coarse aggregate were used; pebbles from Elgin, Ill., and crushed limestone from Chicago. The coarse aggregate in each case was graded up to 1½ in. Sieve analyses and results of other tests of aggregate are given in Table 26.

High calcium lime was used, the same lot as in Series 130.

The 6 by 12-in. concrete cylinders were molded in metal forms. The quantity of materials required for one specimen (about 1/5 cu. ft.) was proportioned and mixed in a batch. Mixing was done by hand with a bricklayer's trowel in shallow galvanized iron pans.

In general the quantity of mixing water was predetermined. The quantity added to compensate for the presence of hydrated lime (or additional cement) was proportional to the quantity of hydrated lime (or cement) and to its normal consistency.

The plasticity or workability of each batch was measured by means of the "flow-table,"[1] using a truncated cone mold 6¾ in. in top diameter, 10 in. in bottom diameter and 5 in. high. The table was raised and dropped 15 times in about 8 seconds. The "flow" is the average base diameter after the completion of the test, expressed as a percentage of the original diameter. The same concrete was used in molding a compression cylinder.

Concrete specimens were stored in a moist room until tested at the age of 28 days.

TEST DATA.

Complete data of the tests are given in Tables 27 to 29. The values of compressive strength and flow are based on the average of 10 or more tests made on different days. Certain studies from the tests are given in Tables 30 to 32.

[1] One design of flow-table is described and illustrated in *Proceedings*, Am. Soc. Testing Materials, Vol. 20, Part 2, p. 242 (1920), and in *"Concrete,"* June, 1920, p. 274.

DISCUSSION OF TESTS.

The following notes point out the principal indications of the tests:

Variations in Tests.—In ten instances, duplicate sets of tests of concrete of the same kind were made independently at different points in the series and on different days (see Table 32). The variation of duplicate averages, each based on ten tests, ranged from 0.31 to 5.96 per cent with a grand average of 2.82 per cent. The maximum variation was somewhat high, but the average gave a value much lower than is generally considered possible in testing a material like concrete. These variations in average values indicate the weight which may be given to any particular test result in this series. It is believed that these tests represent about the limit of accuracy which it is possible to attain in testing concrete without making a very large number of specimens in each set. The same table gives a parallel study of the variation in flow readings. The variation in flow ranged from 0 to 10 per cent with a grand average of 3.8 per cent.

Effect of Hydrated Lime on the Strength of Concrete.—The accompanying tables and figures show the effect of hydrated lime on the strength of concrete for a wide range of mixtures, consistencies, etc. For concrete of the same plasticity, hydrated lime reduced the compressive strength of all mixtures and consistencies used in these tests. It should be noted that these tests were made at 28 days on specimens stored in a damp place. The reduction in strength was nearly proportional to the quantity of lime used. (Note the dotted straight lines in Fig. 16.) The linear reduction in strength due to the addition of hydrated lime was brought out more strikingly in this series than in the earlier tests, probably due to the more accurate averages secured by using ten tests in a set. The few exceptions to this statement which will be found in Fig. 16, particularly in the relative consistency 0.90, do not invalidate the general conclusion, since these discrepancies are generally within the limit of error which may be expected from a single average.

A summary of the reduction in strength of concrete in different groups is given in Table 30. The changes in strength for each 1 per cent addition of hydrated lime in terms of *volume* of cement in the batch were determined from the slopes of the curves in Fig. 16 to 19.

Effect of Small Percentages of Hydrated Lime.—In Groups 3 and 4 quantities of hydrated lime as low as 1 and 2 per cent of the volume of cement were used. The results of these tests are platted in Fig. 18. The relation between strength of the concrete and hydrated lime is represented by a straight line, whether the quantity of mixing water was kept constant and the flow varied (Group 3) or whether the quantity of mixing water was varied and the flow kept constant (Group 4). The additional water required to produce a uniform flow was proportional to the quantity of hydrated lime and its normal consistency. (Compare Fig. 19.) In Group 3, with *water constant* the hydrated lime showed an *increase* in the strength of concrete of 0.61 per cent and the cement an *increase* of 2.37 per cent for each 1 per cent added to the original mixes (by volume). In Group 4, with *flow* constant, the lime showed a *reduction* in strength of 0.34 per cent and the cement an *increase* of 1.00 per cent for each 1 per cent added to the 1 : 4 mix. The increase in strength with the addition of hydrated lime in Group 3 is to be expected; the absorption of water by the lime thus producing a drier concrete as the quantity of lime was increased. The essential feature of these tests is that the use of very small percentages of hydrated lime gave results which differed in no respect from the indications of earlier tests based on percentages varying from 5 to 50 per cent.

Effect of Small Additions of Portland Cement.—Tests in Groups 3 and 4 were carried out for the purpose of studying the effect of portland cement when used as an admixture under exactly the same conditions as hydrated lime. In Group 3 (1 : 5 and 1 : 4 mixtures) the mixing water was kept constant and the flow varied; in Group 4 (1 : 4 mixture) the quantity of the mixing water was increased as cement or lime was added in order to produce a uniform flow. The effect of the addition of small percentages of cement on the strength of concrete was discussed in the preceding paragraph. The addition of portland cement produced the same effect as hydrated lime on the plasticity of the concrete as measured by the flow table (see Fig. 18).

Rich versus Lean Mixtures.—The values in Table 30 show that the rich concrete mixtures suffered a greater reduction in strength due to hydrated lime than lean ones (considering the quantity of hydrated lime to be based on the quantity of cement used). The average reduction (Group 1) ranged from 0.83 per

cent for 1 : 2 mixtures to 0.53 per cent for the 1 : 6 mixture. The tests in this series fully confirm the conclusions of our earlier investigations based on similar tests.

Concrete of Different Consistencies.—The tests in Group 1 show that the wetter mixtures were more affected by hydrated lime than the drier ones. The average reduction in strength for relative consistency 1.50 was 0.83 per cent for each 1 per cent of hydrated lime; for consistency 0.90 the reduction in strength was 0.55 per cent. The average reduction for what may be considered "usual concrete mixtures," that is, 1 : 5 and 1 : 4 mixtures and consistencies 1.00, 1.10 and 1.25 was 0.59 per cent. (Compare 0.50 and 0.56 per cent in original report.)

Pebbles versus Crushed Limestone as Coarse Aggregate.—Tests in Group 2 showed that the type of coarse aggregate had no influence on the effect of hydrated lime. The pebbles and crushed limestone gave almost identical concrete strengths and showed an equal reduction in strength due to the addition of hydrated lime. The pebble concrete showed a somewhat higher flow than the crushed limestone concrete, probably due to the angular particles which have a tendency to exert a greater frictional resistance in the flow test.

Tests with Mixing Water Constant.—With a constant quantity of mixing water in 1 : 4 and 1 : 5 mixtures, hydrated lime showed an increase in strength of 0.61 per cent for each 1 per cent of hydrated lime, as compared with 2.37 per cent for each 1 per cent of portland cement added under the same conditions. As would be expected the concrete became drier as hydrated lime or cement was added.

Tests with Flow Constant.—Hydrated lime showed a reduction in strength of the concrete of 1.34 per cent and the cement an increase in strength of 1.00 per cent for each 1 per cent by volume added to the original 1 : 4 mix, in tests in which the quantity of water was varied in such a way as to produce a constant flow. (See Fig. 18.)

Effect of Quantity of Cement.—The effect of the quantity of cement on the strength of concrete was brought out in Group 1 and in a less pronounced way in Groups 3 and 4. The principal results are shown graphically in Fig. 15 and 16. The strength of concrete increased rapidly with the increase in cement for all consistencies, and regardless of the presence of a given percentage

of hydrated lime. The increase was more pronounced for lean mixtures than for rich. For usual mixtures and consistencies the compressive strength of concrete at 28 days was increased about 1.00 per cent for each 1 per cent increase in cement. Fig. 15 gives cement content as percentages of the volume of concrete and in terms of bags per cubic yard. The inclined dotted lines in Fig. 15 indicate the quantity of cement required for a cubic yard of concrete, due to variations in the consistency and percentage of hydrated lime. The effect of portland cement as an "admixture" is shown in Table 29 and Fig. 18.

Reduction in Strength Due to Certain Percentages of Hydrated Lime.—The reduction in strength of concrete due to certain percentages of hydrated lime is shown in Table 31. These values are based on actual tests in Group 1, and correspond to the inclined dotted lines in Fig. 16, which follow the general slope of the solid lines which are plotted to fit the test data. The percentages of lime are given in percentages of *volume* of aggregate or cement and percentages of *weight* of cement. Where the use of hydrated lime in concrete is recommended it is customary to recommend the use of higher percentages (in terms of the cement) for the leaner mixture; this is about equivalent to a constant percentage of the aggregates. The table shows that for the usual ranges of percentages for ordinary mixtures the presence of hydrated lime may be expected to reduce the strength of concrete about 10 per cent.

Flow Tests.—The "flow-table" was a more satisfactory method of measuring plasticity or workability of concrete in the laboratory than the "slump test"; however, the slump test is believed to be more useful in the field. The variation in the results of flow tests were much more than the strength tests of the concrete (see Table 32). Variations up to 10 points (percentage based on original diameter) may be expected in the average of duplicate sets of 10 tests on identical concrete.

In general the "flow" of lean mixtures was slightly increased and the "flow" of rich mixtures was little affected by the addition of hydrated lime in tests in which the quantity of mixing water was increased in such a manner as to compensate for the presence of hydrated lime. For usual mixtures and consistencies the correction for differences in flow produced an insignificant effect on the reduction in strength of concrete by hydrated lime.

CONCLUSIONS.

The indications of these tests are quite definite and may be stated briefly as follows:

a. Hydrated lime as an admixture reduced the compressive strength of concrete of all mixes and consistencies used in these tests (28-day tests; compare Conclusion 1 in original paper).

b. The reduction of concrete strength was nearly proportional to the quantity of hydrated lime used. (Compare Conclusions 1 and 4 of original report.)

c. Small percentages of hydrated lime (1, 2 and 5 per cent by volume of cement) showed the same rate of reduction in strength as larger percentages (5 to 33 per cent). (See Table 29 and Fig. 18; compare Conclusions 1 and 2 of original report.)

d. For usual concrete mixtures (1 : 4 and 1 : 5, relative consistencies 1.00, 1.10 and 1.25 in Group 1) the average reduction in strength was 0.59 per cent for each 1 per cent of hydrated lime added. Other tests in Groups 2 and 4 gave reductions of 0.62 and 0.34 per cent respectively. Under the same condition the addition of 1 per cent of cement *increased* the strength of concrete about 1 per cent. (Compare Conclusions 2 and 4 of original report.)

e. Rich concrete mixtures showed a greater reduction in strength due to hydrated lime than lean ones. (Compare Conclusion 6 of original report.)

f. The wetter mixes showed a greater loss in strength than dry, due to the addition of hydrated lime. (Compare Conclusion 7 of original report.)

g. Pebbles and crushed limestone as coarse aggregate gave almost identical concrete strengths and showed an equal reduction in strength by the addition of hydrated lime. The pebble concrete showed a higher flow than the crushed-stone concrete.

h. With a *constant quantity of mixing water* in 1 : 4 and 1 : 5 mixes (and of course a variable flow) hydrated lime showed an *increase* in strength of 0.61 per cent for each 1 per cent of lime, as compared with an *increase* of 2.37 per cent for each 1 per cent of portland cement added under the same conditions. (See Table 30 and Fig. 18.)

i. In a single group of tests in which both hydrated lime and portland cement were used as admixtures, and the quantity of mixing water was increased in order to produce concrete of the same plasticity (approximately equal flow) the lime showed a *reduction* in strength of the concrete of 0.34 per cent and the cement an *increase* in strength of 1.00 per cent for each 1 per cent by volume added to the original 1 : 4 mix.

j. Concrete of usual mixtures and consistencies showed an increase in strength of about 1 per cent at 28 days for each 1 per cent of cement added.

k. The mean variation of the average values from duplicate sets of concrete tests each based on 10 specimens made on different days was 1.73 per cent with extreme variations of 0 and 5.96 per cent.

l. The "flow-table" was a more satisfactory method of measuring plasticity or workability of concrete in the laboratory than the "slump test." The variation in the results of flow tests were much greater than the strength tests of the concrete (see Table 32). Variations of 5 to 10 points (percentage based on original diameter) may be expected in duplicate sets of 10 tests on identical concrete.

m. In general, the "flow" of lean concrete mixtures was slightly increased and the "flow" of rich mixtures was little affected by the addition of hydrated lime. For usual mixtures and consistencies the correction for differences in "flow" produced an insignificant effect on the reduction in strength. (Compare Conclusion 10 of original report.)

n. Under identical circumstances the addition of either hydrated lime or portland cement up to 33 per cent produced essentially the same effect on the "flow" of concrete. (See Groups 3 and 4, Table 29 and Fig. 18.)

o. These tests show that for usual concrete mixtures a reduction in strength of about 10 per cent is produced by the addition of hydrated lime in percentages generally recommended by advocates of hydrated lime in concrete.

TABLE 1.—TESTS OF CEMENT.

Tests were made in accordance with the methods of the American Society for Testing Materials.
For cement tests in Series 147, see Table 25.

MISCELLANEOUS TESTS

Cement, Lot No.	Used in Series	Admixture, per cent by weight	Fineness Residue on 200-mesh Sieve	Normal Consistency, per cent by weight	Time of Setting				Soundness Test over Boiling Water
					Vicat Needle		Gillmore Needle		
					Initial h. m.	Final h. m.	Initial h. m.	Final h. m.	
3641	58-59	.....	21.2	23.5	1 30	5 15	3 30	5 40	O. K.
3642	"	10 (sand)[1]	23.2	23.0	1 30	5 15	3 30	5 40	"
3643	"	20 "	23.5	23.0	2 00	5 45	4 15	6 40	"
3644	"	30 "	23.8	23.0	2 00	5 45	4 15	6 40	"
3645	"	40 "	25.0	23.5	2 40	8 00	4 30	8 00	"
3646	"	50 "	25.3	23.0	2 40	7 35	4 30	7 45	"
3647	"	10 (slag)[1]	21.1	23.0	1 45	5 40	4 15	5 50	"
3648	"	20 "	22.0	23.0	3 00	6 15	4 40	7 15	"
3649	"	30 "	22.0	23.0	3 00	6 15	4 40	7 15	"
3650	"	40 "	22.5	23.0	3 05	7 20	5 00	8 00	"
3651	"	50 "	22.0	23.0	3 30	8 00	5 00	8 30	"
4035	100	.....	17.4	23.0	3 50	8 15	5 30	8 50	"
4066	"	.....	20.6	22.0	3 40	6 20	4 00	6 40	"
4013	"	.....	.0	34.0	0 56	4 55	2 15	5 15	"
4135	104	.....	18.0	23.0	. ..	. ..	. ..	. ..	
4235	114	.....	19.9	23.0	3 15	6 05	3 57	7 05	"
4505	130	.....	18.2	21.7	4 40	8 10	5 30	9 15	"
4605	130	.....	18.1	22.8	2 55	6 05	4 00	7 35	"

STRENGTH TESTS

1 : 3 Standard sand mortar.

Specimens stored in water; tested wet.

In general, values for strength are the average of five tests made on different days.

Cement Lot No.	Used in Series	Admixture, per cent by weight	Water, per cent by weight	Tensile Strength (Briquets), lb. per sq in.					Compressive Strength (2 by 4-in. Cylinders), lb. per sq. in.				
				7 d.	28 d.	3 mo.	6 mo.	1 yr.	7 d.	28 d.	3 mo.	6 mo.	1 yr.
3641	58–59	.....	10.4	210	320	330	360	320	1130	1990	2710	3360	3100
3642	"	10 (sand)[1]	10.3	190	290	340	360	340	1190	1920	2660	2970	2300
3643	"	20 "	10.3	180	260	330	340	340	1030	1830	2630	2660	3110
3644	"	30 "	10.3	150	240	300	350	340	790	1420	2130	2380	2270
3645	"	40 "	10.4	130	200	240	290	330	690	990	1720	1850	2040
3646	"	50 "	10.3	70	150	230	250	280	490	890	1380	1470	1620
3647	"	10 (slag)[1]	10.3	210	300	380	420	380	970	2330	3280	3770	2880
3648	"	20 "	10.3	210	310	370	340	370	1010	2070	3050	3150	2980
3649	"	30 "	10.3	180	290	370	350	410	930	1980	2960	3390	3260
3650	"	40 "	10.3	160	260	340	370	380	770	1660	2830	3280	3580
3651	"	50 "	10.3	150	270	390	400	410	630	1520	2840	3030	3400
4035	100	.....	10.3	250	380	400	420	370	1700	2640	3750	4120	3810
4505	130	.....	10.1	195	330	370	350	340	1590	3150	4170	3780	4520
4605	130	.....	10.3	280	390	410	410	395	1950	2880	4170	4600	4170

[1]Admixture added to cement prior to final grinding.

TABLE 2.—MISCELLANEOUS TESTS OF AGGREGATE.

Aggregate: sand and pebbles from Elgin, Ill.

Sieves were made of square mesh wire cloth manufactured by The W. S. Tyler Co. It will be noted that each sieve has a clear opening of twice the width of the preceding sieve.

See Table 11 for sieve analyses of one group of aggregates in Series 114.

Series	Size of Aggregate	Weight, lb. per cu. ft.	Sieve Analysis, per cent coarser than each sieve								Fineness Modulus[1]
			100[a] (0.0058)	48 (0.0116)	28 (0.023)	14 (0 046)	8 (0.093)	4 (0.185)	⅜ (0.37)	¾ (0.75)	1½ (1.5)	
59	0–No. 4	121	65	57	47	35	18	0	..	..	..	2.22
"	"	125	75	68	57	43	25	0	..	..	..	2.68
"	"	126	82	75	65	50	30	0	..	..	..	3.02
"	"	124	88	81	72	57	35	0	..	..	..	3.33
"	"	122	91	86	77	63	38	0	..	..	..	3.55
"	"	119	99	92	82	65	40	0	..	..	..	3.78
"	"	114	97	94	88	75	50	0	..	..	..	4.04
"	"	111	98	96	92	81	57	0	..	..	..	4.24
"	"	101	100	100	100	100	100	0	..	..	..	5.00
100	0–No. 48	102	98	0	..	..	..	..	..	..	..	0.98
"	0–No. 28	102	88	32	0	..	..	..	..	..	..	1.20
130	0–No. 28	102	92	78	0	..	..	..	..	..	..	1.70
100, 114, 130	0–No. 14	106	97	88	35	0	..	..	..	..	..	2.20
100, 114	0–No. 8	108	98	92	50	20	0	..	..	..	..	2.60
100, 114, 130	0–No. 4	112	99	93	63	40	20	0	..	..	..	3.15
100	0–⅜ in.	117	99	94	72	50	28	7	0	..	..	3.50
130	0–⅜ in.	120	99	94	71	60	46	30	0	..	..	4.00
114	0–⅜ in.	121	99	96	79	68	59	49	0	..	..	4.50
130	0–¾ in.	126	100	96	80	73	63	53	35	0	..	5.00
114	0–¾ in.	124	99	97	86	78	71	65	44	0	..	5.40
130	0–1½ in.	125	99	93	68	55	39	23	17	6	0	4.00
130	"	130	99	95	79	70	59	49	37	12	0	5.00
130	"	130	100	95	84	77	70	62	46	16	0	5.50
58, 104, 114, 130	"	127	100	97	86	79	73	68	51	21	0	5.75
130	"	126	100	98	90	85	79	74	56	18	0	6.00
130	"	122	100	98	91	89	85	81	61	20	0	6.25
130	"	118	100	99	94	93	90	87	65	22	0	6.50
130	"	114	100	100	98	96	94	93	70	24	0	6.75

[a]Number of square openings per linear inch or the size of opening in inches.

[1]Sum of percentages in sieve analysis, divided by 100.

TABLE 3.—MISCELLANEOUS TESTS OF POWDERED ADMIXTURES.

Used in Series	Kind	Fineness Residue on each Sieve, per cent by weight				Weight, lb. per cu. ft.	Specific Gravity[1]	Normal Consistency, per cent by weight
		200	100	48	28			
100	Hydrated lime	....	....	....	....	47	2.41	49.0
	Kaolin	....	....	....	....	56	2.51	50.0
	Kieselguhr[2]	....	....	....	....	11	1.92	250.0
	Limestone	21.7	....	....	....	82	2.77	21.0
	Natural cement	24.0	....	....	....	68	2.82	36.0
	Slag	19.5	....	....	....	90	2.88	23.8
104	Hydrated lime	....	....	....	....	47	2.41	49.0
114	Hydrated lime	....	....	....	....	42	2.21	59.0
130	Brick	18.2	6.0	....	....	71	2.70	28.0
	Clay	....	....	....	....	34	2.53	45.0
	Fluorspar	57.0	37.9	13.0	0	135	3.10	15.0
	Gypsum	....	....	....	....	84	2.50	33.2
	Hydrated lime (high calcium)	....	....	....	....	40	2.21	60.0
	Hydrated lime (high magnesium)	....	....	....	....	40	2.48	60.0
	Ironite	91.0	45.0	18.0	0	186	6.90	8.4
	Kaolin	....	....	....	....	47	2.45	45.6
	Kieselguhr	....	....	....	....	13	2.00	230.0
	Lava	21.6	3.8	....	....	109	2.96	19.6
	Limestone	10.0	0.4	....	....	87	2.78	20.8
	Mica	....	....	....	....	48	2.81	....
	Natural cement	6.0	3.0	....	....	68	2.89	40.0
	Pitch	....	....	....	....	42	1.34	63.0
	Sand	20.3	0.2	....	....	90	2.64	22.0
	Slag	19.4	6.0	....	....	114	2 89	20.0
	Tufa	17.8	1.8	....	....	61	2.37	46.0
	Whiting	....	....	....	....	60	2.66	31.0
	Yellow ochre	....	....	....	....	83	3.27	42.0

[1]Values used in calculations for density of concrete. Determinations for the finely powdered admixtures were made with difficulty and they may vary a small amount from the true value.

[2]Same as material now sold under the name of Celite.

TABLE 4.—EFFECT OF HYDRATED LIME ON THE STRENGTH OF CONCRETE.

(Data from Series 130)

Compression tests of 6 by 12-in. cylinders.
Aggregate: sand and pebbles from Elgin, Ill., graded 0-1½ in., fineness modulus, 5.75; for sieve analyses see Table 2.
Admixture added to materials in batch, expressed as percentage of *volume* of cement.
Specimens stored in damp sand until tested.
Each value is the average of five tests made on different days.
Data platted in Fig. 3; see also Table 18.

Hydrated Lime, per cent of cement		Water, ratio to volume of cement						Compressive Strength, lb. per sq. in. (age, 28 days)					
By Volume	By Weight	0.90[1]	1.00	1.10[1]	1.25	1.50	2.00	0.90[1]	1.00	1.10[1]	1.25	1.50	2.00
MIX 1 : 9 BY VOLUME													
0	0	1.11	1.21	1.32	1.47	....	....	1490	1290	1260[2]	960	....	....
5	2.1	1.13	1.23	1.34	1.50	....	....	1300	1320	1160	920	....	....
10	4.2	1.15	1.25	1.36	1.52	....	....	1440	1380	1190[2]	940	....	....
20	8.5	1.19	1.29	1.40	1.57	....	....	1480	1360	1260[2]	910	....	....
33	14.0	1.23	1.34	1.46	1.63	....	....	1370	1300	1070[2]	930	....	....
								Av. 1420	1330	1190	930		
MIX 1 : 6 BY VOLUME													
0	0	0.84	0.92	1.00	1.12	....	....	2400	2250	2230[2]	1620	....	....
5	2.1	0.86	0.94	1.02	1.14	....	....	2350	2390	2120	1670	....	....
10	4.2	0.88	0.96	1.04	1.17	....	....	2510	2480	2170[2]	1620	....	....
20	8.5	0.91	1.00	1.09	1.22	....	....	2480	2420	2190[2]	1620	....	....
33	14.0	0.96	1.05	1.14	1.27	....	....	2430	2310	2070[2]	1430	....	....
								Av. 2430	2370	2160	1590		
MIX 1 : 5 BY VOLUME													
0	0	0.74	0.82	0.89	1.00	1.18	1.54	2970	3040	2670	2040	1260	700
5	2.1	0.76	0.84	0.91	1.03	1.21	1.58	2740	2840	2570	2010	1210	670
10	4.2	0.78	0.86	0.94	1.04	1.24	1.63	2930	3010	2560	2010	1160	680
20	8.5	0.81	0.90	0.97	1.10	1.30	1.70	2910	2820	2430	1900	1020	590
33	14.0	0.86	0.94	1.03	1.16	1.37	1.80	2840	2810	2350	1730	930	490
50	21.3	0.92	1.01	1.10	1.24	1.48	1.93	2770	2600	2200	1600	950	470
								Av. 2860	2850	2460	1880	1090	600
MIX 1 : 4 BY VOLUME													
0	0	0.65	0.72	0.78	0.88	1.04	1.36	3580[2]	3710[2]	3540[2]	2600[2]	1550[2]	800[2]
5	2.1	0.66	0.74	0.80	0.90	1.08	1.40	3940	3600	3320	2570	1320	870
10	4.2	0.69	0.76	0.83	0.93	1.10	1.44	3690	3580	3200	2400	1440	790
20	8.5	0.72	0.80	0.87	0.98	1.16	1.52	3870	3370	2890	2340	1410	790
33	14.0	0.76	0.85	0.92	1.04	1.24	1.62	3390	3000	2600	2040	1340	620
50	21.3	0.82	0.91	1.00	1.12	1.33	1.74	3090	2700	2430	1910	1140	520
								Av. 3590	3320	3000	2300	1370	740
MIX 1 : 3 BY VOLUME													
0	0	0.56	0.62	0.68	0.76	0.90	1.19	4520	4450	4200	3330	2000	1110
5	2.1	0.58	0.64	0.70	0.78	0.93	1.23	4240	4170	3780	3400	2150	1040
10	4.2	0.60	0.66	0.72	0.81	0.96	1.27	3880	4050	3780	3350	2030	1000
20	8.5	0.63	0.70	0.76	0.85	1.02	1.35	3680	4000	3300	3130	1940	760
33	14.0	0.67	0.75	0.82	0.91	1.09	1.45	3750	3460	3080	2520	1560	880
50	21.3	0.73	0.82	0.89	0.99	1.19	1.57	3160	3140	2590	2250	1440	720
								Av. 3870	3880	3460	3000	1850	920
MIX 1 : 2 BY VOLUME													
0	0	0.47	0.52	0.57	0.64	0.77	1.01	5080	4860	4830	3770	2970	1450
5	2.1	0.49	0.54	0.59	0.67	0.80	1.05	5240	4610	4530	3830	2750	1360
10	4.2	0.50	0.56	0.62	0.69	0.83	1.09	5060	4820	4310	3780	2660	1180
20	8.5	0.54	0.60	0.66	0.74	0.88	1.17	4780	4130	3870	3440	2850	1180
33	14.0	0.58	0.65	0.71	0.80	0.96	1.27	3920	4090	3630	3120	2210	1060
50	21.3	0.64	0.71	0.78	0.88	1.06	1.40	3420	3410	3160	2860	2150	890
								Av. 4580	4320	4060	3470	2600	1190

[1]Relative consistency of concrete.
[2]Average of 10 or 15 tests.

TABLE 5.—EFFECT OF HYDRATED LIME ON THE STRENGTH OF CONCRETE.
(Data form Series 130.)

Compression tests of 6 by 12-in. cylinders.
Mix by volume. Relative consistency of concrete, 1.10.
Aggregate: sand and pebbles from Elgin, Ill., graded 0–1½ in., fineness modulus, 5.75.
Admixture added to materials in batch, expressed as percentage of *volume* of cement.
Specimens stored in damp sand; tested damp.
Each value is the average of five tests, unless otherwise noted.
See relative consistency 1.10 in Table 4 for water-ratio of concrete.
Data platted in Fig. 4. See also Table 19.

Hydrated Lime, per cent of cement		Compressive Strength for Different Mixes, lb. per sq. in.					
By Volume	By Weight	1:9	1:6	1:5	1:4	1:3	1:2
		AGE AT TEST, 3 DAYS					
0	0	280	550	770	1030[2]	1280	1790
5	2.1	330	560	790	990	1150	1650
10	4.2	320	610	780	960	1210	1600
20	8.5	300	580	780	830	1130	1470
33	14.0	320	560	680	740	1010	1250
50	21.3	300	480	660	890	1140	1130
		Average 310	560	740	910	1150	1480
		AGE AT TEST, 7 DAYS					
0	0	640	1030	1250	1860[2]	2550	2690
5	2.1	630	1120	1400	1720	2280	2900
10	4.2	620	1170	1420	1880	2170	2610
20	8.5	650	1140	1370	1690	2090	2300
33	14.0	590	1160	1220	1590	1890	2180
50	21.3	610	990	1150	1440	1710	1790
		Average 620	1100	1300	1700	2120	2410
		AGE AT TEST, 28 DAYS[1]					
0	0	1260[2]	2230[2]	2670	3540[2]	4200	4830
5	2.1	1160	2120	2570	3320	3780	4530
10	4.2	1190[2]	2170[2]	2560	3200	3780	4310
20	8.5	1260[2]	2190[2]	2430	2890	3300	3870
33	14.0	1070[2]	2070[2]	2350	2600	3080	3630
50	21.3	1190	1940	2200	2430	2590	3160
		Average 1190	2120	2460	3000	3460	4060
		AGE AT TEST, 3 MONTHS					
0	0	1650	2990	3500	4370[2]	4970	4980
5	2.1	1750	3070	3740	4050	4630	4720
10	4.2	1750	2960	3320	4270	4900	5070
20	8.5	1780	2880	3240	3760	4510	4280
33	14.0	1720	2820	3110	3540	4270	4230
50	21.3	1700	2420	2790	3260	3630	3640
		Average 1720	2860	3280	3880	4480	4490
		AGE AT TEST, 1 YEAR					
0	0	2330	3680	4510	5790[2]	6550	6870
5	2.1	2190	3920	4630	5220	6200	6540
10	4.2	2320	3910	4630	5410	6030	6340
20	8.5	2220	3950	4560	5030	5700	5750
33	14.0	2370	3820	4070	4520	4930	5500
50	21.3	2200	3250	3760	4320	4570	5020
		Average 2270	3780	4360	5050	5660	6000

[1]Same as values for relative consistency 1.10 in Table 4.
[2]Average of 10 or 15 tests.

TABLE 6.—EFFECT OF HYDRATED LIME ON THE STRENGTH OF CONCRETE.

(Series 130.)

Compression tests of 6 by 12-in. cylinders.
Mix by volume. Relative consistency of concrete, 1.10.
Hydrated Lime added to materials in batch; expressed as percentage of *volume* of cement.
Specimens stored in damp sand; tested damp.
Each value is the average of five tests made on different days.
Data platted in Fig. 5 and Table 18.

Fineness Modulus of Aggregate	Hydrated Lime, per cent of cement		Water, ratio to volume of cement					Compressive Strength, lb. per sq. in. (age, 28 days)					
	By Volume	By Weight	1:9	1:6	1:5	1:4	1:3	1:9	1:6	1:5	1:4	1:3	Average
4.00[1]	0	0	1.70	1.26	1.11	0.96	0.81	440	1120	1270	1630	3140	1520
"	10	4.2	1.75	1.30	1.15	1.00	0.85	480	920	1350	2000	3120	1570
"	20	8.5	1.79	1.35	1.20	1.04	0.90	510	960	1420	2010	2940	1570
"	33	14.0	1.85	1.40	1.25	1.10	0.95	500	1000	1420	2130	2860	1580
"	50	21.3	1.90	1.47	1.33	1.17	1.02	550	1060	1370	1860	2380	1440
								Av. 500	1010	1370	1930	2890	1540
5.00[1]	0	0	1.47	1.10	0.97	0.85	0.73	800	1620	2210	2910	3910	2290
"	10	4.2	1.52	1.14	1.01	0.90	0.77	780	1630	2330	3020	3630	2280
"	20	8.5	1.56	1.19	1.06	0.94	0.81	850	1760	2320	2820	3670	2280
"	33	14.0	1.62	1.24	1.11	0.99	0.87	840	1700	2120	2570	3080	2060
"	50	21.3	1.67	1.31	1.19	1.07	0.94	900	1500	2040	2400	2560	1880
								Av. 830	1640	2200	2740	3370	2140
5.50[1]	0	0	1.36	1.03	0.92	0.80	0.69	1100	2040	2790	3370	4280	2720
"	10	4.2	1.40	1.07	0.96	0.85	0.73	1090	2050	2660	3320	3980	2620
"	20	8.5	1.44	1.12	1.00	0.89	0.77	1100	2060	2620	3090	3560	2490
"	33	14.0	1.50	1.17	1.06	0.94	0.83	1080	2060	2330	2890	3120	2300
"	50	21.3	1.56	1.24	1.13	1.02	0.90	1080	1980	2070	2540	3050	2140
								Av. 1090	2040	2490	3040	3600	2450
5.75[1]	0	0	1.32	1.00	0.89	0.78	0.68	1260[2]	2230[2]	2670	3540[2]	4200	2780
"	10	4.2	1.36	1.04	0.94	0.83	0.72	1190[2]	2170[2]	2560	3200	3780	2580
"	20	8.5	1.40	1.09	0.97	0.87	0.76	1260[2]	2190[2]	2430	2890	3300	2410
"	33	14.0	1.46	1.14	1.03	0.92	0.82	1070[2]	2070[2]	2350	2600	3080	2230
"	50	21 3	1.52	1.21	1.10	1.00	0.89	1190[2]	1190[2]	2200	2430	2590	1920
								Av. 1190	1970	2440	2930	3390	2380
6.00[1]	0	0	1.27	0.96	0.86	0.76	0.66	1260	2100	2710	3390	4430	2780
"	10	4.2	1.31	1.00	0.90	0.80	0.70	1240	2150	2530	3370	3850	2630
"	20	8.5	1.36	1.05	0.95	0.84	0.74	1210	2100	2450	3150	3530	2490
"	33	14.0	1.41	1.10	1.00	0.90	0.80	1140	1950	2450	2820	3350	2340
"	50	21.3	1.47	1.17	1.07	0.97	0.87	1100	1830	2270	2730	3090	2200
								Av. 1190	2030	2480	3090	3650	2490
6.25[1]	0	0	1.22	0.93	0.84	0.74	0.65	1140	1940	2500	3150	4080	2560
"	10	4.2	1.26	0.98	0.88	0.78	0.69	990	1840	2340	3130	3810	2420
"	20	8.5	1.31	1.02	0.92	0.82	0.73	970	1960	2280	3280	3520	2400
"	33	14.0	1.36	1.07	0.98	0.88	0.79	980	1810	2190	2980	3170	2230
"	50	21.3	1.44	1.14	1.05	0.95	0.86	950	1730	2020	2680	2810	2040
								Av. 1010	1860	2270	3040	3480	2330
6.50[1]	0	0	1.18	0.90	0.81	0.72	0.63	740	1610	2000	2790	3490	2130
"	10	4.2	1.23	0.94	0.85	0.76	0.67	860	1550	2200	2780	3600	2200
"	20	8.5	1.27	0.98	0.90	0.80	0.71	700	1480	1990	3110	3250	2110
"	33	14.0	1.33	1.04	0.95	0.86	0.77	870	1760	2170	2810	3340	2190
"	50	21.3	1.39	1.11	1.03	0.93	0.84	770	1580	2090	2690	2800	1990
								Av. 790	1600	2090	2840	3300	2120
6.75[1]	0	0	....	....	....	0.70	0.62	....	....	....	2540	3470	....
"	10	4.2	....	....	....	0.74	0.66	....	....	....	2430	3340	....
"	20	8.5	....	....	....	0.78	0.70	....	....	....	2390	3100	....
"	33	14.0	....	....	....	0.84	0.76	....	....	....	2460	3040	....
"	50	21.3	....	....	....	0.91	0.83	....	....	....	2470	2630	....
								Av.	....	....	2460	3120	....

[1]All aggregate sand and pebbles from Elgin, Ill., graded 0–1½ in. Different values of fineness modulus were obtained by varying the proportions of sand and pebbles. For sieve analysis see Table 2.

[2]Average of 10 or 15 tests.

TABLE 7.—EFFECT OF HYDRATED LIME ON THE STRENGTH OF CONCRETE.

Compression tests of 6 by 12-in. cylinders.
Aggregate: sand and pebbles from Elgin, Ill.
Admixture added to materials in batch; expressed as percentage of *volume* of cement.
Specimens stored in damp sand; tested damp.
Each value is the average of five tests made on different days.
See Table 2 for sieve analysis of aggregates.

Hydrated Lime, per cent of cement		For Different Sizes of Aggregates													
		Water, ratio to volume of cement							Compressive Strength, lb. per sq. in. (age, 28 days)						
Volume	Weight	0–28	0–14	0–8	0–4	0–⅜	0–¾	0–1½	0–28	0–14	0–8	0–4	0–⅜	0–¾	0–1½
1 : 5 MIX. RELATIVE CONSISTENCY, 1.10. SERIES 130.															
0	0	1.52	1.42	....	1.26	1.10	0.97	0.89	470	540	....	1010	1490	2140	2670
5	2.1	1.54	1.44	....	1.28	1.12	0.99	0.91	440	550	....	990	1600	2340	2570
10	4.2	1.56	1.47	....	1.31	1.15	1.01	0.94	450	570	....	980	1620	2440	2560
20	8.5	1.60	1.51	....	1.35	1.19	1.05	0.97	500	630	....	1050	1630	2260	2430
33	14.0	1.65	1.57	....	1.40	1.24	1.11	1.04	460	600	....	1070	1530	1870	2350
50	21.3	1.73	1.64	....	1.47	1.32	1.18	1.10	530	660	....	1050	1560	1740	2200
Av.	.....	....	....	....	....	....	....	....	480	590		1020	1570	2130	2460
1 : 4 MIX. RELATIVE CONSISTENCY, 1.10. SERIES 130.															
0	0	1.29	1.21	....	1.09	0.95	0.85	0.78	760	840	....	1360	2130	2820	3540[2]
5	2.1	1.31	1.23	....	1.11	0.97	0.87	0.80	690	830	....	1490	2300	2900	3320
10	4.2	1.33	1.26	....	1.13	0.99	0.89	0.83	750	950	....	1480	2250	2680	3200
20	8.5	1.38	1.30	....	1.18	1.04	0.94	0.87	760	880	....	1540	2260	2720	2890
33	14.0	1.43	1.35	....	1.23	1.09	0.99	0.92	740	940	....	1520	2230	2460	2600
50	21.3	1.50	1.43	....	1.30	1.16	1.06	1.00	850	980	....	1330	1900	2420	2430
Av.	.....	.....	.....	.....	.....	.....	.....	.....	760	900		1450	2180	2670	3000
1 : 4 MIX. RELATIVE CONSISTENCY, 1.00. SERIES 114.															
0	0	....	1.13	1.07	1.00	0.83	0.77	0.73	....	970	1170	1360	2490	3530	3310
5	2.2	....	1.15	1.09	1.02	0.85	0.79	0.75	....	990	1140	1420	2640	3250	3470
10	4.5	....	1.17	1.11	1.04	0.87	0.81	0.77	....	950	1180	1440	2580	3290	3300
20	8.9	....	1.21	1.15	1.08	0.91	0.85	0.81	....	950	1160	1520	2600	2910	3090
33	14.7	....	1.26	1.20	1.13	0.96	0.90	0.86	....	1020	1200	1560	2480	2630	2670
50	22.3	....	1.33	1.27	1.20	1.03	0.97	0.93	....	1060	1290	1610	2330	2390	2500
Av.	.....	.....	.....	.....	.....	.....	.....	.....	.....	990	1190	1480	2520	3000	3060

[1]Average of 15 tests.

TABLE 8.—EFFECT OF NATURAL CEMENT ON THE STRENGTH OF PORTLAND CEMENT CONCRETE—SERIES 130.

Compression tests of 6 by 12-in. cylinders.
Mix 1 volume of *portland* cement to 4 volumes of mixed aggregate.
Aggregate: sand and pebbles from Elgin, Ill., graded 0–1½ in.; fineness modulus 5.75; see Table 2.
Natural cement added to materials in batch; expressed as percentage of *volume* of portland cement.
Specimens stored in damp sand; tested damp.
Each value is the average of five tests made on different days.

Natural Cement, per cent of Portland Cement		Compressive Strength, lb. per sq. in.											
		For Different Ages. Relative Consistency, 1.10					For Different Relative Consistencies. Age at Test, 28 days						
Volume	Weight	3 d.	7 d.	28 d.	3 mo.	1 yr.	0.90	1.00	1.10	1.25	1.50	2.00
0	0	1030[1]	1860[1]	3540[1]	4370[1]	5790[1]	3580[1]	3710[1]	3540[1]	2600[1]	1550[1]	800[1]
10	7.2	1080	1850	2970	4130	5790	3450	3320	2970	2190	1530	740
20	14.5	1080	1720	2910	4110	5410	3380	3680	2910	2200	1480	700
33	23.9	1050	1620	2820	3950	5370	3560	3400	2820	2180	1380	650
50	36.2	960	1610	2800	3640	4950	3250	2990	2800	1980	1120	660
75	54.3	920	1510	2400	3380	4650	2930	2930	2400	1970	1240	570
Natural cement only[2]	...	810	1360	2320	3170	4330	2760	2440	2320	1650	1270	520

[1]Average of 10 or 15 tests.

[2]This mixture is on the same basis as the portland cement mixture containing *no* natural cement, that is, the proportions are one volume of cement and four volumes of mixed aggregate. It should be noted that the other mixtures in this table are on a somewhat different basis, in that the quantity of portland cement is constant.

TABLE 9.—EFFECT OF STORAGE CONDITION ON THE STRENGTH OF CONCRETE CONTAINING HYDRATED LIME—SERIES 114.

Compression tests of 6 by 12-in. concrete cylinders.
1 : 4 mix by volume; hand-mixed concrete; relative consistency, 1.00.
Aggregate: sand and pebbles from Elgin, Ill., graded 0–1½ in.
Hydrated lime was added as a percentage of the volume of the cement.
Each value is the average of five tests made on different days.
Data platted in Fig. 9.

Age at Test	Compressive Strength of Concrete Stored in Damp Sand for Times Indicated, Remainder in Air																			
	Strength, lb. per sq. in.										Strength, per cent									
	Damp Sand[1]	1[2] d.	2 d.	4 d.	7 d.	14 d.	28 d.	3 mo.	6 mo.	1 yr.	1[2] d.	2 d.	4 d.	7 d.	14 d.	28 d.	3 mo.	6 mo.	1 yr.
HYDRATED LIME, 0 per cent																				
7 days	2090	1890	2010	1930	2090	....	....	....	....	....	90	96	92	100	....	....	....	....	....	....
14 days	2750	2410	2690	2750	2770	2750	....	....	....	....	88	98	100	100	100	....	....	....	....	....
21 days	3100	....	....	....	....	3230	....	....	....	....	....	....	....	....	104	....	....	....	....	....
28 days	3400	2980	3020	3070	3670	3780	3400	....	....	....	88	89	91	108	111	100	....	....	....	....
2 mo.	4100	....	....	....	....	....	4200	....	....	....	....	....	....	....	....	102	....	....	....	....
3 mo.	4300	2910	3390	3560	3950	4590	4600	4300	....	....	68	79	83	92	107	107	100	....	....	....
3.5 mo	4500	....	....	....	....	....	....	4730	....	....	....	....	....	....	....	....	105	....	....	....
6 mo.	4800	....	....	....	....	....	4350	5320	4800	....	....	....	....	....	....	91	111	100	....	....
7 mo.	4900	....	....	....	....	....	....	....	5500	....	....	....	....	....	....	....	....	112	....	....
9 mo.	5000	....	....	....	....	....	....	4810	5680	....	....	....	....	....	....	....	97	113	....	....
12 mo.	5150	2740	3010	3290	3750	4040	4350	5340	5770	5150	53	58	64	73	78	84	104	112	100	....
13 mo.	5170	....	....	....	....	....	....	....	....	5920	....	....	....	....	....	....	....	....	115	....
15 mo.	5200	....	....	....	....	....	....	....	....	6400	....	....	....	....	....	....	....	....	123	....
18 mo.	5220	....	....	....	....	....	....	....	....	6570	....	....	....	....	....	....	....	....	126	....
2 yr.	5300	3300	3390	3670	3570	4050	4460	4980	5760	6260	62	64	69	67	76	84	94	109	118	....
5 yr.	5370	3230	3300	3910	3610	3680	3650	4560	4990	5370	60	61	73	67	68	68	85	93	100	....
HYDRATED LIME, 10 per cent																				
7 days	2010	1850	1830	2120	2010	....	....	....	....	....	92	91	106	100	....	....	....	....	....	....
14 days	2700	2260	2500	2920	2940	2700	....	....	....	....	84	93	108	108	100	....	....	....	....	....
21 days	3050	....	....	....	....	3270	....	....	....	....	....	....	....	....	108	....	....	....	....	....
28 days	3300	2770	2930	3380	3300	3770	3300	....	....	....	84	89	102	100	114	100	....	....	....	....
2 mo.	3900	....	....	....	....	....	4340	....	....	....	....	....	....	....	....	111	....	....	....	....
3 mo.	4250	3120	3220	3620	4130	4550	4390	4250	....	....	73	76	85	97	107	104	100	....	....	....
3.5 mo	4350	....	....	....	....	....	....	4430	....	....	....	....	....	....	....	....	102	....	....	....
6 mo.	4700	....	....	....	....	....	4060	4660	4700	....	....	....	....	....	....	86	99	100	....	....
7 mo.	4800	....	....	....	....	....	....	....	5700	....	....	....	....	....	....	....	....	119	....	....
9 mo.	4880	....	....	....	....	....	....	4610	5340	....	....	....	....	....	....	....	95	109	....	....
12 mo.	4950	3190	3010	3440	3950	3850	4510	5230	5910	4950	64	61	69	80	78	91	106	120	100	....
13 mo.	5000	....	....	....	....	....	....	....	....	5650	....	....	....	....	....	....	....	....	113	....
15 mo.	5020	....	....	....	....	....	....	....	....	6160	....	....	....	....	....	....	....	....	123	....
18 mo.	5050	....	....	....	....	....	....	....	....	6320	....	....	....	....	....	....	....	....	126	....
2 yr.	5120	3370	3280	3460	4040	4200	4150	4920	5960	6040	66	64	68	79	82	81	96	116	118	....
5 yr.	5210	3380	2870	3670	3930	4060	3910	4510	4980	5490	65	55	70	75	78	75	87	96	105	....
HYDRATED LIME, 33 per cent																				
7 days	1680	1570	1680	1740	1680	....	....	....	....	....	93	100	104	100	....	....	....	....	....	....
14 days	2200	2080	2140	2320	2410	2200	....	....	....	....	95	97	106	110	100	....	....	....	....	....
21 days	2450	....	....	....	....	2680	....	....	....	....	....	....	....	....	110	....	....	....	....	....
28 days	2650	2330	2450	2750	3040	2940	2650	....	....	....	88	92	104	115	111	100	....	....	....	....
2 mo.	3200	....	....	....	....	....	3680	....	....	....	....	....	....	....	....	115	....	....	....	....
3 mo.	3500	2680	2660	3230	3790	3880	3990	3500	....	....	76	76	92	108	111	114	100	....	....	....
3.5 mo.	3600	....	....	....	....	....	....	3890	....	....	....	....	....	....	....	....	108	....	....	....
6 mo.	4000	....	....	....	....	....	3810	4460	4000	....	....	....	....	....	....	95	112	100	....	....
7 mo.	4100	....	....	....	....	....	....	....	4460	....	....	....	....	....	....	....	....	109	....	....
9 mo.	4300	....	....	....	....	....	....	4520	4940	....	....	....	....	....	....	....	105	115	....	....
12 mo.	4500	2440	2560	3300	3420	3660	4060	4590	5400	4500	54	57	73	76	82	90	102	120	100	....
13 mo.	4600	....	....	....	....	....	....	....	....	4960	....	....	....	....	....	....	....	....	108	....
15 mo.	4700	....	....	....	....	....	....	....	....	5230	....	....	....	....	....	....	....	....	112	....
18 mo.	4800	....	....	....	....	....	....	....	....	5410	....	....	....	....	....	....	....	....	113	....
2 yr.	5020	2790	2860	3300	3610	3930	4020	4970	5370	5740	56	57	66	72	78	80	99	107	114	....
5 yr.	5700	2890	2770	3190	3380	3500	3790	4120	4740	4670	51	49	56	59	61	66	72	83	82	....

[1]Specimens stored in damp sand until test. Values interpolated from age-strength curves.
[2]Period stored in damp sand; stored in air remainder of time before test.

TABLE 10.—EFFECT OF HYDRATED LIME ON THE COMPRESSIVE AND BOND STRENGTH OF CONCRETE—SERIES 104.

Compression tests of 6 by 12-in. cylinders.
Pull-out tests on 1-in. plain round bar embedded in 8 by 8-in. cylinder.
Mix, 1 : 5 by volume; relative consistency, 1.00.
Aggregate: sand and pebbles from Elgin, Ill., graded 0–1½ in.
Specimens stored in damp sand; tested damp.
Each value is the average of five tests made on different days.
In this group of tests the hydrated lime *replaced* an equal volume of cement; therefore the *quantity* of *cement* decreased with increased percentage of hydrated lime. In all later tests hydrated lime was *added* to a fixed quantity of cement.

Hydrated Lime, per cent of cement plus hydrated lime		Water-Ratio[1]	Compressive Strength, lb. per sq. in.				Maximum Bond Stress, lb. per sq. in.			
By Volume	By Weight		7 d.	28 d.	3 mo.	1 yr.	7 d.	28 d.	3 mo.	1 yr.
0	0	0.88	1310	2730[2]	3550	4020	310	680[2]	760	910
5	2.6	0.91	1310	2410	3730	4120	300	660	740	940
10	5.3	0.96	1230	2660	3530	4000	380	630	710	910
20	11.1	1.08	1120	2280	2950	3800	370	510	720	860
33	19.8	1.30	810	1720	2260	3080	170	370	450	620
50	33.4	1.72	520	1030	1470	1510	160	280	460	400

[1]Ratio of volume of mixing water to volume of cement.
[2]Average of 15 tests made on 15 different days.

TABLE 11.—EFFECT OF HYDRATED LIME ON THE STRENGTH AND WEAR OF CONCRETE—SERIES 114.

Compression tests of 6 by 12-in. cylinders.
Mix 1 : 4 by volume. Relative consistency, 1.10.
Aggregate: sand and pebbles from Elgin, Ill., graded 0–1½ in.
Hydrated lime added to materials in batch; expressed as per cent by *volume* of cement.
Specimens stored in damp sand; tested damp.
Each value for compression is the average of 5 tests made on different days; for wear average of 15 tests made on 3 different days.

Reference No.[1]	Sieve Analysis of Aggregate, Amount Coarser than Each Sieve, per cent by weight									Aggregate		For Different Percentages of Hydrated Lime					
												Compressive Strength, lb. per sq. in. (age, 28 days)			Depth of Wear, in. (age, 3 months)		
	No. 100	No. 48	No. 28	No. 14	No. 8	No. 4	⅜ in.	¾ in.	1½ in.	Fineness Modulus[2]	Surface Area[3]	0 (0.78)[4]	10 (0.83)[4]	33 (0.92)[4]	0 (0.78)[4]	10 (0.83)[4]	33 (0.92)[4]
264	95	89	82	75	67	67	67	62	0	6.04	1565	2780	2620	2310	0.50	0.44	0.50
268	98	95	90	83	83	83	50	22	0	6.04	834	2530	2540	2280	0.48	0.46	0.60
269	98	94	90	86	83	80	55	18	0	6.04	898	2590	2610	2220	0.56	0.46	0.53
270	96	90	80	80	80	80	60	38	0	6.04	1391	2570	2660	2100	0.51	0.54	0.50
274	90	85	81	78	75	73	66	56	0	6.04	1992	2580	2410	2320	0.48	0.46	0.53
275	100	93	82	73	73	73	63	47	0	6.04	1076	2880	2610	2290	0.49	0.45	0.52
276	100	100	100	92	81	60	45	26	0	6.04	390	2930	2640	2460	0.52	0.52	0.58
279	100	99	96	91	80	50	50	38	0	6.04	514	3040	2700	2280	0.47	0.44	0.55
281	99	98	91	86	80	76	38	38	0	6.04	701	3030	2700	2480	0.46	0.56	0.58
284	99	98	91	85	80	76	67	8	0	6.04	685	2690	2790	2440	0.52	0.51	0.62
												Av. 2760	2630	2320	0.50	0.48	0.55
Minimum value												2530	2410	2100	0.46	0.44	0.50
Maximum value												3040	2790	2480	0.56	0.56	0.62
Mean variation from average, per cent												6.2	2.7	3.7	4.6	7.9	6.4

[1]Same as the numbers in Table 2, *Bulletin 1* of the Structural Materials Research Laboratory, Lewis Institute, Chicago.
[2]Fineness modulus of aggregate; sum of the percentages in the sieve analysis, divided by 100.
[3]Surface area of aggregate; square inches per pound of aggregate. See "Proportioning the Materials of Mortars and Concretes by Surface Areas of Aggregates," by L. N. Edwards, *Proceedings*, Am. Soc. Testing Materials, Vol. 18, Part 2 (1918).
[4]Ratio of mixing water to volume of cement.

TABLE 12.—EFFECT OF HYDRATED LIME IN CONCRETE USING A CONSTANT WATER-RATIO.

(Data from Series 114)

Compression tests of 6 by 12-in. cylinders.

Aggregate: sand and pebbles from Elgin, Ill., graded 0–1½ in.

Hydrated lime added to material in batch; expressed as percentage of *volume* of cement.

Specimens stored in damp sand; tested damp.

Each value is the average of five tests made on different days.

Sufficient water for normal consistency was used for 50 per cent hydrated lime; the same quantity was used for other percentages, consequently as the percentage of hydrated lime decreased, the concrete was of higher relative consistency.

Hydrated Lime, per cent of cement		Compressive Strength, lb. per sq. in. (age, 28 days)		
By Volume	By Weight	1 : 5 (1.03)[1]	1 : 4 (0.93)[1]	1 : 3 (0.83)[1]
0	0	1990	2140	2640
5	2.2	1710	2320	2570
10	4.5	1990	2110	2560
20	8.9	1970	2410	2470
33	14.7	2170	2410	2610
50	22.3	2080	2260	2560
Average		1980	2280	2570
Minimum value		1710	2110	2470
Maximum value		2170	2410	2640
Mean variation from average, per cent		4.97	4.60	1.49

[1]Water in batch, ratio to volume of cement.

TABLE 13.—EFFECT OF POWDERED ADMIXTURES ON THE STRENGTH OF CONCRETE.

(Data from Series 130)

Compression tests of 6 by 12-in. cylinders. Mix 1 : 4 by volume.
Age at test, 28 days.
Aggregate: sand and pebbles from Elgin, Ill., graded 0–1½ in., fineness modulus, 5.75.
Admixture added to materials in batch; expressed as percentage of *volume* of cement.
Each value is the average of five tests made on different days, unless otherwise noted.

Admixture, per cent of cement by volume	Compressive Strength for Different Admixtures lb. per sq. in.														
	Brick	Clay	Fluorspar	Hydrated Lime[1]	Kaolin	Kieselguhr[4]	Lava	Limestone	Natural Cement[2]	Sand	Slag	Tufa	Whiting	Yellow Ochre	Average
RELATIVE CONSISTENCY, 1.00															
0[3]	3710	3710	3710	3710	3710	3710	3710	3710	3710	3710	3710	3710	3710	3710	3710
5	3590	3540	3240	3600	3730	3510	3660	3230	3650	3510	3460	3470	3490	3390	3500
10	3700	3520	3450	3580	3620	3440	3770	3640	3320	3420	3810	3420	3560	3600	3560
20	3630	3490	3210	3370	3290	3420	3370	3540	3680	3320	3810	3250	3580	3160	3440
33	3550	3460	3050	3000	2950	3260	3080	3200	3400	3020	3920	3150	3330	2880	3240
50	3430	3260	2600	2700	2730	2900	3000	2780	2990	3040	3850	2720	3160	2360	2970
Average....	3600	3500	3210	3330	3340	3370	3430	3350	3460	3340	3760	3290	3470	3180	3410
RELATIVE CONSISTENCY, 1.10															
0[3]	3540	3540	3540	3540	3540	3540	3540	3540	3540	3540	3540	3540	3540	3540	3540
5	3420	3510	3230	3320	3380	3310	3280	3340	3350	3190	3400	3200	3360	3560	3340
10	2980	3410	3190	3200	3450	3470	3070	3200	2970	3180	3230	3100	3280	3440	3220
20	3230	3110	2890	2890	3060	3140	3080	3050	2910	3080	3540	2960	3350	2950	3090
33	3350	3000	2740	2600	2830	2710	2760	2640	2820	2890	3520	2720	2970	2650	2880
50	3060	2640	2520	2430	2250	2500	2660	2590	2800	2610	3590	2350	2750	2160	2640
Average....	3260	3200	3020	3000	3080	3110	3060	3060	3060	3080	3470	2980	3210	3040	3120
RELATIVE CONSISTENCY, 1.25															
0[3]	2600	2600	2600	2600	2600	2600	2600	2600	2600	2600	2600	2600	2600	2600	2600
5	2850	2720	2350	2570	2710	2530	2570	2570	2490	2800	2640	2280	2550	2570	2580
10	2680	2820	2280	2400	2710	2400	2530	2420	2190	2510	2780	2560	2510	2640	2530
20	2810	2650	2390	2340	2530	2380	2420	2480	2200	2430	2700	2330	2560	2370	2470
33	2720	2500	2040	2040	2430	2180	2160	2250	2180	2380	2690	2200	2280	2060	2290
50	2570	2490	2060	1910	1970	1840	2070	2180	1980	2170	2840	2000	2240	1660	2140
Average....	2700	2630	2280	2310	2490	2320	2390	2410	2270	2480	2700	2320	2450	2310	2430
RELATIVE CONSISTENCY, 1.50															
0[3]	1550	1550	1550	1550	1550	1550	1550	1550	1550	1550	1550	1550	1550	1550	1550
5	1670	1790	1430	1320	1840	1570	1410	1500	1480	1650	1590	1660	1490	1550	1570
10	1610	1710	1420	1440	1730	1550	1470	1480	1530	1500	1540	1410	1540	1510	1530
20	1480	1680	1430	1410	1750	1410	1240	1410	1480	1470	1660	1370	1470	1610	1490
33	1590	1810	1390	1340	1730	1380	1350	1360	1380	1410	1470	1290	1590	1480	1470
50	1710	1700	1230	1140	1480	1230	1230	1300	1120	1270	1600	1160	1540	1170	1350
Average....	1600	1700	1400	1360	1680	1440	1370	1430	1420	1470	1560	1400	1520	1470	1490
GRAND AVERAGE OF ALL CONSISTENCIES															
0	2850	2850	2850	2850	2850	2850	2850	2850	2850	2850	2850	2850	2850	2850	2850
5	2880	2890	2560	2700	2920	2730	2730	2660	2740	2790	2770	2650	2720	2770	2750
10	2740	2860	2580	2660	2880	2720	2710	2680	2500	2650	2840	2620	2720	2800	2710
20	2790	2730	2480	2500	2660	2590	2530	2620	2570	2580	2930	2480	2740	2520	2620
33	2800	2690	2300	2240	2480	2380	2340	2360	2440	2420	2900	2340	2540	2270	2420
50	2690	2520	2100	2040	2110	2120	2240	2210	2220	2270	2970	2060	2420	1840	2280
Average....	2790	2760	2480	2500	2650	2560	2570	2560	2550	2590	2880	2500	2660	2510	2600

[1]High calcium hydrated lime.
[2]Values for 5 per cent natural cement interpolated.
[3]Average of 10 or 15 tests. The same value is repeated in each column.
[4]Same as material now sold under the name of Celite.

TABLE 14.—EFFECT OF POWDERED ADMIXTURES ON THE STRENGTH OF CONCRETE—SERIES 130.

Compression tests of 6 by 12-in. cylinders. Mix by volume. Relative consistency, 1.10.
Aggregate: sand and pebbles from Elgin, Ill., graded 0–1½ in., fineness modulus, 5.75.
Admixture added to materials in batch; expressed as percentage of *volume* of cement.
Specimens stored in damp sand; tested damp.
Each value is the average of five tests made on different days, unless otherwise noted.

Admixture, per cent of cement by volume	Mix by Volume	Age at Test	High Calcium Hydrated Lime	High Magnesium Hydrated Lime	Kaolin	Kieselguhr[3]	Limestone	Natural Cement	Sand	Slag	Tufa	Whiting
0	1 : 9	28 days	1260[1]	....	1220[1]	1220[1]	1220[1]	....	1220[1]	1220[1]	1220[1]	1220[1]
5			1160[1]	....	1160	1120	990	....	1240	1230	1250	1140
10			1190[1]	....	1230	1140	1040	....	1130	1190	1100	1160
20			1260[1]	....	1330	1170	1040	....	1180	1340	1170	1240
33			1070[1]	....	1430	1110	1100	....	1250	1420	1120	1340
50			1190	....	1430	1170	1120	....	1210	1510	1170	1360
Average			1190		1300	1160	1080		1200	1320	1170	1240
0	1 : 5	28 days	2670[1]	....	2670[1]	2670[1]	2670[1]	....	2670[1]	2670[1]	2670[1]	2670[1]
5			2570	....	2700	2520	2450	....	2450	2460	2490	2420
10			2560	....	2670	2490	2540	....	2500	2580	2440	2630
20			2430	....	2620	2450	2490	....	2370	2730	2510	2580
33			2350	....	2310	2260	2420	....	2230	2610	2270	2600
50			2200	....	2280	2140	2270	....	2080	2640	2000	2410
Average			2460		2540	2420	2470		2380	2620	2400	2550
0	1 : 3	28 days	4200[1]	....	4200[1]	4200[1]	4200[1]	....	4200[1]	4200[1]	4200[1]	4200[1]
5			3780	....	3520	4110	3830	....	3760	3800	3650	3620
10			3780	....	3550	3630	3700	....	3580	3780	3600	3680
20			3300	....	3230	3330	3620	....	3370	3670	3230	3520
33			3080	....	2930	3220	3530	....	3190	3650	2900	3250
50			2590	....	2570	2760	2900	....	2850	3440	2630	3090
Average			3460		3330	3540	3630		3490	3760	3370	3560
0	1 : 4	3 days	1030[1]	1030[1]	1030[1]	1030[1]	1030[1]	1030[1]	1030[1]	1030[1]	1030[1]	1030[1]
5			990	1100	1040	920	1050	1060	1050	1030	1080	1120
10			960	1050	1110	950	1050	1080	1100	1020	960	1060
20			830	1020	1040	870	1140	1080	1060	1020	950	1090
33			740	910	990	710	1110	1050	1080	1020	820	1060
50			890	900	830	700	1010	960	980	950	690	1060
Average			910	1000	1010	860	1060	1040	1050	1010	920	1070
0	1 : 4	7 days	1860[1]	1860[1]	1860[1]	1860[1]	1860[1]	1860[1]	1860[1]	1860[1]	1860[1]	1860[1]
5			1720	1850	1950	1760	1790	1850[2]	1850	1890	1630	1770
10			1880	1820	1910	1550	2030	1850	1730	1620	1730	1800
20			1690	1770	1870	1500	1780	1720	1660	1920	1690	1760
33			1590	1660	1570	1380	1740	1620	1700	1820	1450	1700
50			1440	1360	1420	1130	1500	1610	1470	1760	1300	1550
Average			1690	1720	1760	1530	1780	1750	1710	1810	1610	1740
0	1 : 4	28 days	3540[1]	3540[1]	3540[1]	3540[1]	3540[1]	3540[1]	3540[1]	3540[1]	3540[1]	3540[1]
5			3320	3350	3380	3310	3340	3400[2]	3190	3400	3200	3360
10			3200	3240	3450	3470	3200	2970	3180	3230	3100	3280
20			2890	3180	3060	3140	3050	2910	3080	3540	2960	3350
33			2600	2650	2830	2710	2640	2820	2890	3520	2720	2970
50			2430	2380	2250	2500	2590	2800	2610	3590	2350	2750
Average			3000	3060	3080	3110	3060	3070	3080	3470	2980	3210
0	1 : 4	3 mo.	4370[1]	4370[1]	4370[1]	4370[1]	4370[1]	4370[1]	4370[1]	4370[1]	4370[1]	4370[1]
5			4050	4390	4220	4240	3980	4260[2]	4360	4210	4260	4160
10			4270	4240	4130	4260	4200	4130	4260	4260	4140	3990
20			3760	3750	3730	3560	4000	4110	4030	4460	4080	3780
33			3540	3490	3390	3390	3640	3950	3480	4630	3940	3680
50			3260	3090	2640	3040	3360	3640	3280	4600	3730	3600
Average			3880	3890	3750	3810	3920	4080	3960	4420	4090	3930
0	1 : 4	1 yr.	5790[1]	5790[1]	5790[1]	5790[1]	5790[1]	5790[1]	5790[1]	5790[1]	5790[1]	5790[1]
5			5220	5400	5350	5340	4990	5790	5930	5470	5620	5370
10			5410	5290	5360	5220	5290	5790	5290	5700	5840	5040
20			5030	5170	4830	4960	5060	5410	4920	6120	5400	4830
33			4520	4720	4460	4370	4930	5370	4690	6150	5490	4810
50			4320	3980	3840	4140	4530	4950	4580	6290	5340	4670
Average			5050	5060	4940	4970	5100	5520	5200	5920	5580	5080

[1]Average of 10 or 15 tests.
[2]Values for 5 per cent natural cement obtained by interpolation.
[3]Same as material now sold under the name of Celite.

TABLE 15.—EFFECT OF POWDERED ADMIXTURES ON THE STRENGTH OF CONCRETE.

(Data from Series 130)

Compression tests of 6 by 12-in. cylinders.
Mix 1 : 4 by volume. Relative consistency 1.10.
Aggregate: sand and pebbles from Elgin, Ill., graded 0–1½ in., fineness modulus, 5.75.
Admixture added to materials in batch; expressed as percentage of *volume* of cement.
Specimens stored in damp sand; tested damp.
Each value is the average of five tests made on different days.

Admixture, per cent of cement, by volume	Water, ratio to volume of cement					Compressive Strength, lb. per sq. in.				
	Hydrated Lime	Gypsum	Mica	Pitch	Ironite	Hydrated Lime	Gypsum	Mica	Pitch	Ironite
AGE AT TEST, 3 DAYS										
0[1]	0.78	0.78	0.78	0.78	0.78	1030	1030	1030	1030	1030
1	0.78	0.79	0.78	0.79	0.78	....	1290	1140	1110	1120
2	0.79	0.79	0.78	0.79	0.79	....	1270	1070	1030	1100
5	0.80	0.81	0.78	0.80	0.80	990	650	1110	1050	1170
10	0.83	0.83	0.78	0.82	0.81	960	470	1120	950	1070
20	0.88	0.88	0.78	0.87	....	830	420	970	800	....
						Average	860	1070	1000	....
AGE AT TEST, 7 DAYS										
0[1]	0.78	0.78	0.78	0.78	0.78	1860	1860	1860	1860	1860
1	0.78	0.79	0.78	0.79	0.78	....	1850	1830	1850	1840
2	0.79	0.79	0.78	0.79	0.79	....	1900	1860	1910	1810
5	0.81	0.81	0.78	0.80	0.80	1720	810	1860	1760	1700
10	0.83	0.83	0.78	0.82	0.81	1880	640	1860	1570	1600
20	0.88	0.88	0.78	0.87	....	1690	570	1520	1300	....
						Average	1270	1800	1710	....
AGE AT TEST, 28 DAYS										
0[1]	0.78	0.78	0.78	0.78	0.78	3540	3540	3540	3540	3540
1	0.78	0.79	0.78	0.79	0.78	....	3440	3270	3490	3280
2	0.79	0.79	0.78	0.79	0.79	....	3350	3570	3120	3230
5	0.81	0.81	0.78	0.80	0.80	3320	2830	3330	3130	3120
10	0.83	0.83	0.78	0.82	0.81	3200	980	3420	3050	3220
20	0.88	0.88	0.78	0.87	....	2890	860	2710	2590	....
						Average	2500	3310	3150	....
AGE AT TEST, 3 MONTHS										
0[1]	0.78	0.78	0.78	0.78	0.78	4370	4370	4370	4370	4370
1	0.78	0.79	0.78	0.79	0.78	....	4420	4290	4500	4050
2	0.79	0.79	0.78	0.79	0.79	....	4330	4370	4480	4390
5	0.81	0.81	0.78	0.80	0.80	4050	4080	4190	4120	4310
10	0.83	0.83	0.78	0.82	0.81	4270	1230	4050	4000	4090
20	0.88	0.88	0.78	0.87	....	3760	800	3200	3390	....
						Average	3200	4080	4140	....
AGE AT TEST, 1 YEAR										
0[1]	0.78	0.78	0.78	0.78	0.78	5790	5790	5790	5790	5790
1	0.78	0.79	0.78	0.79	0.78	....	5570	5800	5640	5510
2	0.79	0.79	0.78	0.79	0.79	....	5570	5650	5810	5620
5	0.81	0.81	0.78	0.80	0.08	5220	5610	5710	5180	5700
10	0.83	0.83	0.78	0.82	0.81	5410	3990	5300	5070	5570
20	0.88	0.88	0.78	0.87	....	5030	....[2]	4250	4600	....
						Average	....	5420	5350	....

[1]Average of 10 tests.
[2]Disintegrated.

TABLE 16.—EFFECT OF HYDRATED LIME ON THE PLASTICITY OF CONCRETE.
(Data from Series 130.)

Slump tests of 6 by 12-in. concrete cylinders.
Aggregate: sand and pebbles from Elgin, Ill., graded 0–1½ in., fineness modulus, 5.75.
Cement: a mixture of five brands purchased in the Chicago market.
Admixture added to cement.
Each value is the average of five tests made on different days.

Concrete Mix by Volume	Admixture, per cent of cement		Slump of Concrete for Different Relative Consistencies, in.						
	By Volume	By Weight	0.90	1.00	1.10	1.25	1.50	2.00	Av.
1:9	0	0	4.6	6.2	2.1	1.5	...	...	...
	5	2.1	4.5	2.6	0.3	0.2	...	...	...
	10	4.2	4.7	1.5	1.5	1.5	...	...	...
	20	8.5	4.8	1.7	0.2	1.6	...	...	...
	33	14.0	0.6	0.2	0.3	4.0	...	...	...
			Av. 3.8	2.4	0.9	1.8			..
1:6	0	0	1.7	0.3	2.0	4.0	...	...	...
	5	2.1	3.1	0.3	3.0	5.5	...	...	...
	10	4.2	1.4	0.3	1.8	5.6	...	...	...
	20	8.5	0.2	0.5	2.1	7.8	...	...	...
	33	14.0	0.3	0.5	5.0	7.8	...	...	...
			Av. 1.3	0.4	2.8	6.1			
1:5	0	0	0.2	0.3	2.0	6.7	7.5	8.6	4.2
	5	2.1	1.1	0.4	4.9	7.8	6.9	8.6	5.0
	10	4.2	0.1	0.5	5.8	7.4	8.5	7.6	5.0
	20	8.5	0.2	2.2	5.0	5.7	8.4	9.0	5.1
	33	14.0	0.2	1.9	6.1	8.0	9.0	9.2	5.7
	50	21.3	0.3	1.9	6.8	8.6	9.6	10.0	6.2
			Av. 0.4	1.2	5.1	7.4	8.3	8.8	5.2
1:4	0	0	1.2	0.7	6.1	6.8	7.4	8.7	5.2
	5	2.1	0.1	1.2	6.8	8.2	8.9	8.7	5.6
	10	4.2	0.2	2.0	5.9	8.3	9.0	9.2	5.8
	20	8.5	1.5	3.1	6.4	8.3	9.4	9.4	6.4
	33	14.0	0.4	3.1	7.2	8.9	9.1	9.5	6.4
	50	21.3	0.3	1.4	6.1	8.6	9.4	10.0	6.0
			Av. 0.6	1.9	6.4	8.2	8.9	9.3	5.9
1:3	0	0	0.2	4.2	6.5	8.3	9.3	9.8	6.4
	5	2.1	0.2	1.7	6.3	8.7	9.2	7.9	5.7
	10	4.2	0.3	2.3	6.6	8.4	9.0	9.8	6.1
	20	8.5	1.2	3.0	6.4	8.5	9.5	9.9	6.4
	33	14.0	0.3	3.3	6.5	8.4	9.6	10.0	6.4
	50	21.3	0.3	2.4	6.2	8.8	9.8	10.1	6.3
			Av. 0.4	2.8	6.4	8.5	9.4	9.6	6.2
1:2	0	0	0.2	1.2	6.8	8.8	9.4	9.8	6.0
	5	2.1	0.4	3.0	6.6	9.1	9.9	9.9	6.5
	10	4.2	0.4	2.1	7.1	9.1	10.0	10.4	6.5
	20	8.5	0.2	2.1	5.5	8.7	9.8	10.1	6.1
	33	14.0	0.2	1.0	5.1	8.3	9.8	10.4	5.8
	50	21.3	0.1	0.9	4.8	8.1	9.9	10.6	5.7
			Av. 0.3	1.7	6.0	8.7	9.8	10.2	6.1
Av. 1:5, 1:4, 1:3, 1:2	0	0	0.4	1.6	5.4	7.6	8.4	9.2	5.5
	5	2.1	0.4	1.6	6.2	8.4	8.7	8.8	5.7
	10	4.2	0.2	1.7	6.4	8.3	9.1	9.2	5.8
	20	8.5	0.8	2.6	5.8	7.8	9.3	9.6	6.0
	33	14.0	0.3	2.3	6.2	8.4	9.4	9.8	6.1
	50	21.3	0.2	1.6	6.0	8.5	9.7	10.2	6.0
			Av. 0.4	1.9	6.0	8.2	9.1	9.5	5.8

TABLE 17.—REDUCTION IN STRENGTH OF CONCRETE BY HYDRATED LIME.

(Effect of Size of Aggregate—Series 114 and 130.)

Compression tests of 6 by 12-in. concrete cylinders.
28-day tests of hand-mixed concrete.
Reduction in strength calculated from slope of curves drawn from data in Table 7.
Compare Tables 18 and 19.

Series	Mix. by Volume	Relative Consistency	Percentage Reduction in Strength for Each 1 per cent Hydrated Lime, in terms of volume of cement						
			0 to No. 28	0 to No. 14	0 to No. 8	0 to No. 4	0 to ⅜ in.	0 to ¾ in.	0 to 1½ in.
114	1:4	1.00	....	+0.21	+0.18	+0.32	0.20	0.64	0.58
130	1:4	1.10	+0.44	+0.24	....	0	0.22	0.32	0.60
130	1:5	1.10	+0.22	+0.54	....	0	+0.06	0.50	0.34

NOTE: + indicates increase in strength.

TABLE 18.—REDUCTION IN STRENGTH OF CONCRETE BY HYDRATED LIME.

(Effect of Consistency and Grading of Aggregate)

Compression tests of 6 by 12-in. concrete cylinders.
Reduction in strength calculated from average slope of curves in figures indicated.
Age at test 28 days.
Compare Tables 17 and 19.

Relative Consistency	Aggregate		Age at Test, days.	Percentage Reduction in Strength for Each 1 per cent Hydrated Lime, in terms of volume of cement							Values Calculated from
	Size, in.	Fineness Modulus.[1]		1:9	1:6	1:5	1:4	1:3	1:2	Average	
0.90	0–1½	5.75	28	+0.12	+0.12	0.10	0.38	0.54	0.62	0.41[3]	Fig. 3
1.00				0	0	0.28	0.48	0.58	0.60	0.48[3]	
1.10				0.15	0.25	0.32	0.60	0.68	0.66	0.56[3]	
1.25				0	0.42	0.48	0.62	0.64	0.60	0.58[3]	
1.50				....	....	0.56	0.56	0.64	0.66	0.60[3]	
2.00				....	....	0.72	0.62	0.70	0.66	0.68[3]	
				[4]Av.0.01	0.14	0.29	0.52	0.61	0.62	0.56	
1.10	0–1½	4.00	28	+0.04	0	0	0	0.40	....	0.07	Fig. 5
		5.00		+0.12	0.12	0.16	0.42	0.70	....	0.25	
		5.50		0	0	0.52	0.48	0.66	....	0.32	
		5.75		0.34	0.30	0.36	0.56	0.76	....	0.46	
		6.00		0.24	0.32	0.28	0.44	0.64	....	0.38	
		6.25		0.22	0.20	0.32	0.38	0.64	....	0.35	
		6.50		0.12	0	0	0.20	0.42	....	0.14	
		6.75[2]		....	....	....	0	0.44	....	....	
				Av.0.11	0.14	0.24	0.35	0.61	....	0.29	

NOTE: +indicates increase in strength.

[1] Fineness modulus of aggregate: the sum of the percentages in the sieve analysis, divided by 100. See Table 2 for sieve analysis of aggregates.

[2] Omitted from average.

[3] Mixes 1:9 and 1:6 omitted from average.

[4] Relative consistencies 1.50 and 2.00 omitted from average.

TABLE 19.—REDUCTION IN STRENGTH OF CONCRETE BY HYDRATED LIME.

Compression tests of 6 by 12-in. concrete cylinders.
Reduction in strength calculated from average slope of curves in figures indicated.
Compare Tables 17 and 18.

Mix by Volume	Relative Consistency	Aggregate		Percentage Reduction in Strength for Each 1 per cent Hydrated Lime, in terms of volume of cement								Values Calculated from
		Size, in.	Fineness Modulus	3 days	7 days	28 days	3 mo.	1 year	2 years	5 years	Av.	
1 : 4	0.90	0–1½	5.75	....	0.52	0.56	0.54	0.54	0.44	0.43	0.50	Fig. 1
	0.95			....	0.50	0.50	0.54	0.50	0.53	0.57	0.52	
	1.00			....	0.62	0.66	0.60	0.44	0.62	0.58	0.59	
	1.05			....	0.42	0.50	0.56	0.50	0.66	0.42	0.51	
	1.10			....	0.40	0.68	0.52	0.40	0.49	0.28	0.46	
	1.25			....	0.44	0.60	0.52	0.32	0.32	0.27	0.41	
	1.50			....	0.46	0.52	0.66	0.66	0.53	0.44	0.54	
	2.00			....	0.74	0.74	0.56	0.58	0.50	0.58	0.62	
				Av....	0.52	0.56	0.56	0.50	0.51	0.43	0.51	
1 : 9	1.00	0–1½	5.75	....	+0.82	+0.18	+0.12	+0.24	+0.34	+0.40	+0.35	Fig. 2
1 : 6				....	....	0.14[1]	....	....	....	....	....	
1 : 5				....	0	0.50	0.52	0.46	0.23	0.29	0.33	
1 : 4				....	0.58	0.60	0.62	0.40	0.62	0.58	0.57	
1 : 3				....	0.85	0.60	0.55	0.61	0.60	0.63	0.64	
1 : 2				....	....	0.66[1]	....	....	....	....	....	
				Av.....	0.15	0.38	0.39	0.31	0.28	0.28	0.30	
1 : 9	1.10	0–1½	5.75	0.22	0.16	0.15	0	0.11	....	....	0.13	Fig. 4
1 : 6				0.24	0.12	0.25	0.36	0.29	....	....	0.25	
1 : 5				0.26	0.22	0.32	0.44	0.30	....	....	0.31	
1 : 4				0.30	0.40	0.60	0.52	0.50	....	....	0.46	
1 : 3				0.40	0.58	0.68	0.46	0.59	....	....	0.54	
1 : 2				0.64	0.72	0.66	0.52	0.57	....	....	0.62	
				Av.0.34	0.36	0.44	0.38	0.39	....	....	0.38	
1 : 4[2]	1.10	0–1½	5.75	0.30	0.40	0.60	0.52	0.50	....	....	0.46	
1 : 4[3]				0.36	0.52	0.62	0.62	0.55	....	....	0.56	
				Av.0.33	0.46	0.61	0.57	0.58	....	....	0.51	

NOTE: + indicates increase in strength.
[1] Omitted from average.
[2] High calcium hydrated lime.
[3] High magnesium hydrated lime.

TABLE 20.—EFFECT OF POWDERED ADMIXTURES ON THE WEAR OF CONCRETE —SERIES 130.

Wear tests of 8 by 8 by 5-in. blocks. Mix 1 : 4 by volume. Relative consistency, 1.10.
Aggregate: sand and pebbles from Elgin, Ill., graded 0–1¼ in., fineness modulus, 5.75.
Powdered admixture added to materials in batch; expressed as percentage of *volume* of cement
Specimens tored in damp sand 14 days, remainder in air. Age at test, 3 months.
Wear tests made in Talbot-Jones rattler.
Each value is the average of 15 tests made in groups of five on three different days, unless otherwise noted

Admixture, per cent of cement by volume	Wear for Different Admixtures, inches						
	Hydrated Lime (High Calcium)[1]	Kieselguhr[3]	Powdered Limestone	Powdered Slag	Powdered Sand	Natural Cement	Average
0[2]	0.40	0.40	0.40	0.40	0.40	0.40	0.40
5	0.36	0.41	0.45	0.41	0.36	0.38	0.40
10	0.40	0.43	0.45	0.42	0.42	0.38	0.42
20	0.45	0.43	0.41	0.36	0.39	0.44	0.41
33	0.49	0.52	0.42	0.39	0.38	0.42	0.44
Average	0.42	0.44	0.43	0.40	0.39	0.40	0.41

[1]Values from 1 : 4 mix in Table 21.

[2]Average of 30 tests made in groups of five on six different days. The same value is repeated in each column.

[3]Same as material now sold under the name of Celite.

TABLE 21.—EFFECT OF HYDRATED LIME ON THE WEAR OF CONCRETE.

(Data from Series 130)

Wear tests of 8 by 8 by 5-in. blocks.
Mix by volume. Relative consistency, 1.10.
Aggregate: sand and pebbles from Elgin, Ill., graded 0–1½ in., fineness modulus 5.75.
Hydrated lime added to materials in batch; expressed as percentage of *volume* of cement.
Specimens stored in damp sand 14 days; remainder in air.
Age at test, 3 months.
Wear tests made in Talbot-Jones rattler.
Each value is the average of 15 tests, made in groups of five, on three different days, unless otherwise noted.

Hydrated Lime, per cent of cement by volume	Wear for Different Mixtures, inches					
	1 : 4½	1 : 4	1 : 3½	1 : 3	1 : 2½	Average
0[1]	0.40	0.40	0.38	0.38	0.34	0.38
5	0.39	0.36	0.39	0.37	0.33	0.37
10	0.39	0.40	0.38	0.39	0.36	0.38
20	0.46	0.45	0.40	0.40	0.38	0.42
33	0.48	0.49	0.41	0.46	0.44	0.46
Average	0.42	0.42	0.39	0.40	0.37	0.40

[1]Average of 30 tests made in groups of five on six different days.

TABLE 22.—EFFECT OF HYDRATED LIME ON THE YIELD AND DENSITY OF CONCRETE—SERIES 130.

6 by 12-in. cylinders.
Aggregate: sand and pebbles from Elgin, Ill., graded 0–1½ in., fineness modulus, 5.75.
Admixture added to materials in batch; expressed as percentage of *volume* of cement.
Yield is the volume of concrete produced by one volume of mixed aggregate.
Density is the total solid material in the mass.
Yield and density were calculated from weights determined immediately on removal of the cylinders from the forms. See Table 23 for other data on yield and density.
See Table 4 for water-ratio and strength tests.

Hydrated Lime, per cent of cement		For Different Relative Consistencies											
		Yield of Concrete						Density of Concrete					
By Volume	By Weight	0.90	1.00	1.10	1.25	1.50	2.00	0.90	1.00	1.10	1.25	1.50	2.00
MIX 1 : 9 BY VOLUME													
0	0	0.988	0.992	0.991	0.985	.....	.....	0.834	0.831	0.832	0.837	.....	.....
5	2.1	0.997	0.995	0.979	0.993	.....	.....	0.828	0.826	0.843	0.832	.....	.....
10	4.2	0.998	0.997	1.002	1.009	.....	.....	0.829	0.829	0.825	0.829	.....	.....
20	8.5	0.984	0.983	0.987	0.997	.....	.....	0.843	0.844	0.840	0.832	.....	.....
33	14.0	0.997	0.995	1.000	1.009	.....	.....	0.837	0.838	0.835	0.828	.....	.....
Average.....		0.993	0.992	0.992	0.999	.....	.....	0.834	0.834	0.835	0.832	.....	.....
MIX 1 : 6 BY VOLUME													
0	0	1.016	1.003	1.008	1.023	.....	.....	0.838	0.847	0.845	0.831	.....	.....
5	2.1	1.013	1.011	1.016	1.026	.....	.....	0.841	0.844	0.840	0.832	.....	.....
10	4.2	1.017	1.016	1.021	1.030	.....	.....	0.842	0.843	0.838	0.831	.....	.....
20	8.5	1.023	1.023	1.030	1.044	.....	.....	0.840	0.840	0.835	0.823	.....	.....
33	14.0	1.026	1.031	1.038	1.053	.....	.....	0.845	0.840	0.835	0.822	.....	.....
Average.....		1.019	1.017	1.023	1.015	.....	.....	0.841	0.843	0.839	0.828	.....	.....
MIX 1 : 5 BY VOLUME													
0	0	1.040	1.032	1.032	1.049	1.062	1.106	0.833	0.839	0.839	0.826	0.816	0.784
5	2.1	1.037	1.031	1.043	1.053	1.067	1.120	0.839	0.843	0.833	0.825	0.815	0.777
10	4.2	1.050	1.043	1.048	1.056	1.080	1.120	0.832	0.837	0.833	0.827	0.808	0.779
20	8.5	1.043	1.043	1.056	1.067	1.090	1.137	0.842	0.842	0.833	0.824	0.806	0.773
33	14.0	1.055	1.061	1.075	1.092	1.110	1.161	0.840	0.835	0.824	0.811	0.798	0.763
50	21.3	1.083	1.090	1.096	1.116	1.144	1.181	0.827	0.822	0.818	0.803	0.783	0.758
Average.....		1.051	1.050	1.058	1.072	1.092	1.138	0.836	0.836	0.830	0.819	0.804	0.772
MIX 1 : 4 BY VOLUME													
0	0	1.063	1.063	1.077	1.094	1.110	1.151	0.837	0.837	0.828	0.814	0.802	0.774
5	2.1	1.069	1.076	1.082	1.099	1.126	1.160	0.837	0.832	0.827	0.815	0.795	0.772
10	4.2	1.068	1.082	1.089	1.106	1.130	1.174	0.841	0.830	0.825	0.812	0.795	0.764
20	8.5	1.076	1.092	1.107	1.125	1.144	1.199	0.842	0.828	0.818	0.804	0.790	0.755
33	14.0	1.111	1.120	1.129	1.140	1.178	1.217	0.823	0.817	0.810	0.802	0.777	0.752
50	21.3	1.136	1.153	1.163	1.183	1.207	1.241	0.816	0.802	0.796	0.782	0.767	0.746
Average.....		1.087	1.098	1.108	1.124	1.149	1.190	0.833	0.824	0.817	0.805	0.788	0.760
MIX 1 : 3 BY VOLUME													
0	0	1.140	1.132	1.142	1.160	1.187	1.236	0.817	0.823	0.817	0.803	0.786	0.754
5	2.1	1.148	1.140	1.156	1.176	1.203	1.246	0.816	0.822	0.810	0.797	0.778	0.752
10	4.2	1.147	1.154	1.162	1.182	1.211	1.262	0.822	0.815	0.810	0.796	0.777	0.746
20	8.5	1.168	1.176	1.185	1.205	1.238	1.294	0.814	0.809	0.802	0.788	0.768	0.734
33	14.0	1.209	1.203	1.221	1.242	1.277	1.328	0.797	0.800	0.789	0.775	0.755	0.726
50	21.3	1.241	1.238	1.256	1.278	1.306	1.380	0.789	0.791	0.780	0.767	0.750	0.710
Average.....		1.176	1.174	1.187	1.207	1.237	1.291	0.809	0.810	0.801	0.788	0.769	0.737
MIX 1 : 2 BY VOLUME													
0	0	1.281	1.275	1.276	1.300	1.345	1.417	0.790	0.794	0.794	0.778	0.752	0.714
5	2.1	1.293	1.278	1.297	1.313	1.359	1.431	0.788	0.798	0.786	0.775	0.750	0.712
10	4.2	1.310	1.297	1.310	1.332	1.381	1.456	0.783	0.791	0.783	0.770	0.742	0.705
20	8.5	1.360	1.318	1.349	1.366	1.403	1.507	0.765	0.790	0.772	0.762	0.742	0.692
33	14.0	1.406	1.364	1.396	1.416	1.469	1.546	0.754	0.777	0.759	0.748	0.721	0.685
50	21.3	1.444	1.437	1.452	1.478	1.537	1.611	0.750	0.754	0.746	0.733	0.705	0.672
Average.....		1.349	1.328	1.347	1.368	1.416	1.495	0.772	0.784	0.773	0.761	0.735	0.697

TABLE 23.—EFFECT OF HYDRATED LIME ON THE YIELD AND DENSITY OF CONCRETE.

6 by 12-in. cylinders.

Aggregate: sand and pebbles from Elgin, Ill., graded 0–1½ in., fineness modulus, 5.75.

Admixture added to materials in batch; expressed as percentage of *volume* of cement.

Yield is the volume of concrete produced by one volume of mixed aggregate.

Density is the total solid material in the mass.

Yield and density were calculated from weights determined immediately on removal of the cylinders from the forms.

Each value is the average of five tests made on different days.

See Table 22 for other data on yield and density of concrete.

Hydrated Lime, per cent of cement		For Different Sizes of Aggregate													
		Yield of Concrete							Density of Concrete						
By Volume	By Weight	0 to No. 28	0 to No. 14	0 to No. 8	0 to No. 4	0 to ⅜ in.	0 to ¾ in.	0 to 1½ in.	0 to No. 28	0 to No. 14	0 to No. 8	0 to No. 4	0 to ⅜ in.	0 to ¾ in.	0 to 1½ in.
1 : 5 CONCRETE. RELATIVE CONSISTENCY, 1.10. SERIES 130															
0	0	1.151	1.140	.....	1.077	1.076	1.060	1.032	0.633	0.649	.....	0.716	0.762	0.806	0.839
5	2.1	1.157	1.127	.....	1.091	1.064	1.050	1.043	0.633	0.661	.....	0.709	0.772	0.817	0.833
10	4.2	1.162	1.133	.....	1.104	1.070	1.055	1.048	0.632	0.658	.....	0.703	0.770	0.816	0.833
20	8.5	1.156	1.126	.....	1.106	1.079	1.077	1.056	0.641	0.669	.....	0.708	0.769	0.805	0.833
33	14.0	1.157	1.122	.....	1.101	1.089	1.083	1.075	0.647	0.677	.....	0.717	0.769	0.807	0.824
50	21.3	1.168	1.148	.....	1.110	1.099	1.143	1.096	0.649	0.671	.....	0.720	0.772	0.773	0.818
Average.....		1.158	1.132	.....	1.098	1.080	1.078	1.058	0.639	0.664	.....	0.712	0.769	0.804	0.830
1 : 4 CONCRETE. RELATIVE CONSISTENCY, 1.10. SERIES 130															
0	0	1.136	1.159	.....	1.121	1.106	1.100	1.077	0.663	0.660	.....	0.709	0.762	0.799	0.828
5	2.1	1.168	1.147	.....	1.111	1.105	1.091	1.082	0.648	0.671	.....	0.719	0.766	0.809	0.827
10	4.2	1.166	1.154	.....	1.118	1.102	1.097	1.089	0.652	0.668	.....	0.717	0.771	0.807	0.825
20	8.5	1.180	1.167	.....	1.130	1.123	1.116	1.107	0.649	0.668	.....	0.716	0.762	0.800	0.818
33	14.0	1.196	1.173	.....	1.146	1.137	1.137	1.129	0.650	0.672	.....	0.715	0.762	0.795	0.810
50	21.3	1.224	1.196	.....	1.164	1.157	1.163	1.163	0.644	0.670	.....	0.713	0.760	0.786	0.796
Average.....		1.178	1.166	.....	1.132	1.122	1.117	1.108	0.651	0.668	.....	0.715	0.764	0.799	0.817
1 : 4 CONCRETE. RELATIVE CONSISTENCY, 1.00. SERIES 114															
0	0	.....	1.116	1.110	1.096	1.065	1.042	1.050	.....	0.672	0.691	0.723	0.794	0.828	0.842
5	2.2	.....	1.117	1.112	1.100	1.065	1.048	1.057	.....	0.675	0.693	0.724	0.798	0.828	0.841
10	4.5	.....	1.120	1.113	1.102	1.071	1.060	1.062	.....	0.676	0.695	0.725	0.796	0.821	0.838
20	8.9	.....	1.132	1.127	1.103	1.093	1.073	1.080	.....	0.674	0.693	0.730	0.786	0.818	0.831
33	14.7	.....	1.144	1.142	1.122	1.112	1.093	1.098	.....	0.676	0.691	0.726	0.780	0.811	0.828
50	22.3	.....	1.170	1.162	1.142	1.131	1.130	1.123	.....	0.671	0.689	0.724	0.778	0.795	0.820
Average.....		.....	1.133	1.128	1.110	1.089	1.074	1.078	.....	0.674	0.692	0.725	0.789	0.817	0.833

TABLE 24.—OUTLINE OF TESTS—SERIES 147.

Compression tests of 6 by 12-in. cylinders. Mix by loose volume.

Cement: a mixture of 5 brands of portland cement purchased in Chicago.

Aggregate: sand and pebbles from Elgin, Ill., and crushed limestone from Chicago. In all cases the mixed aggregate was graded 0–1½ in.

High-calcium hydrated lime was added to the materials in the batch; expressed as a percentage of volume of cement. In Groups 3 and 4 portland cement was considered as an admixture in the same way as hydrated lime.

The plasticity of the fresh concrete was measured by means of the "Flow-table," using a truncated cone mold 6¾ in. top diameter, 10 in. bottom diameter and 5 in. high. The table was dropped 15 times in about 8 seconds. The "flow" is expressed in per cents of the original base diameter.

Specimens stored in moist room until date of test.

Ten specimens for each condition were made on different days.

Series begun August 17, 1920. Finished October 20, 1920.

Group	Aggregate: Kind	Aggregate: Fineness Modulus	Mix by Volume	Admixture: Material	Admixture: Per Cent of Volume of Cement	Relative Consistency	Age at Test, Days	Number of Tests: In a Set	Number of Tests: Total
1	Sand and Pebbles..	5.75	1 : 6 1 : 5 1 : 4 1 : 3 1 : 2	Hydrated Lime	0 5 10 20 33	0.90 1.00 1.10 1.25 1.50	28	10	1250
2	Sand and Pebbles Sand and Crushed Limestone	5.50 5.75[1]	1 : 4	Hydrated Lime	0 5 10 20 33	1.10	28	10	150
3	Sand and Pebbles..	5.75	1 : 5 1 : 4	Hydrated Lime Portland Cement	0 1 2 5 10 20 33	1.25 (Note 1)	28	10	280
4	Sand and Pebbles..	5.75	1 : 4	Hydrated Lime Portland Cement	0 1 2 5 10 20 33	1.10 (Note 2)	28	10	140
								Total	1820

[1]Sand and crushed limestone only; compare with similar values for sand and pebbles in Group 1.

NOTE 1.—In Group 3 calculate the quantity of mixing water for the original mixes. *Use the same quantity of water* after adding hydrated lime or cement.

NOTE 2.—In Group 4 calculate quantity of mixing water for original mix. For concrete containing hydrated lime and additional cement *use quantity of water required to give the same "flow"* as the original mix.

TABLE 25.—TESTS OF CEMENT.

The cements used consisted of mixtures of equal parts of 5 brands of portland cement purchased in Chicago.

1 : 3 Standard Sand Mortar.

All tests were made according to the Standard Specifications and Tests for Portland Cement (Serial Designation: C9-21) of the American Society for Testing Materials.

Cement Lot No.	Fineness Residue on No. 200 Sieve	Normal Consistency, per cent by weight	Time of Setting: Vicat Needle: Initial h m	Time of Setting: Vicat Needle: Final h m	Time of Setting: Gillmore Needle: Initial h m	Time of Setting: Gillmore Needle: Final h m	Soundness Test (over Boiling Water)	Mixing Water, per cent	Briquets: Tensile Strength, lb. per sq. in.: 7 da.	28 da.	3 mo.	6 mo.	2 by 4-in. Cylinders: Compressive Strength, lb. per sq. in.: 7 da.	28 da.	3 mo.	6 mo.
4951	18.2	22.6	5 00	8 25	6 45	9 50	OK	10.3	270	360	420	390	2220	3740	4340	4840
5075	18.8	22.5	3 20	8 45	5 45	9 00	OK	10.3	250	350	420	445	1710	3010	4020	3640

TABLE 26.—SIEVE ANALYSIS OF AGGREGATES.

Sieves manufactured by the W. S. Tyler Co., Cleveland, Ohio.

Sieve Number or Size	Size of Clear Opening, in.	Amounts Coarser than Each Sieve, per cent by weight				
		Sand	Pebbles	Crushed Limestone	Mixed Aggregate	
					5.50[1]	5.75[1]
No. 100	0.0058	97	100	100	99	99
No. 48	0.0116	85	100	100	94	95
No. 28	0.023	57	100	100	84	87
No. 14	0.046	38	100	100	78	81
No. 8	0.093	15	100	100	68	74
No. 4	0.185	2	100	100	64	70
⅜ in.	0.37	..	75	75	47	52
¾ in.	0.75	..	25	25	16	17
Fineness Modulus		2.94	7.00	7.00	5.50	5.75
Unit weight, lb. per cu. ft.		112	110	96	130[2] 124[2]	128[2] 123[2]

[1]Fineness modulus of mixed aggregates.

[2]The upper values are for mixtures of sand and pebbles; the lower values for mixtures of sand and crushed limestone.

TABLE 27.—EFFECT OF HYDRATED LIME IN CONCRETE.

(Data from Group 1 Series 147)

Compression tests of 6 by 12-in. cylinders. Age at test, 28 days.

Aggregate: sand and pebbles from Elgin, Ill., graded 0–1½ in.

Concrete for each specimen mixed by hand in 1/5 cu. ft. batch.

The plasticity of the fresh concrete was measured by means of the "flow-table." (See Table 24 for further details.)

Specimens stored in moist room until day of test.

Each value is the average of 10 tests made on different days.

Hydrated Lime, Per cent of Volume of Cement	"Flow" of Concrete of Different Relative Consistencies					Compressive Strength of Concrete of Different Relative Consistencies, lb. per sq. in.				
	0.90	1.00	1.10	1.25	1.50	0.90	1.00	1.10	1.25	1.50
MIX 1 : 6 BY VOLUME										
0	146	170	195	217	222	2630	2270	1830	1490	980
5	149	180	203	220	230	2680	2180	1980	1430	900
10	147	182	204	226	231	2560	2190	1870	1300	890
20	152	187	212	232	232	2470	2080	1740	1240	790
33	149	194	223	235	236	2310	1930	1520	1160	650
Average	149	183	207	226	230	2530	2130	1790	1380	840
MIX 1 : 5 BY VOLUME										
0	143	182	215	232[1]	254[2]	3350	2890	2450	1860[1]	1100
5	143	188	217	237	254[2]	3460	3020	2580	1700	1060
10	140	194	216	232	254[2]	3380	2890	2370	1660	1050
20	145	194	217	238	254[2]	3140	2780	2300	1620	960
33	142	196	225	241	254[2]	3180	2590	2110	1470	940
Average	143	191	218	236	254[2]	3300	2830	2360	1660	1020
MIX 1 : 4 BY VOLUME										
0	148	192	225[1]	244[1]	254[2]	4080	3600	3270[1]	2440[1]	1590
5	151	191	222	243	254[2]	4290	3600	3200	2360	1460
10	147	191	224	242	254[2]	4180	3520	3090	2170	1400
20	154	204	231	254[2]	254[2]	3780	3260	2760	1880	1180
33	144	200	233	254[2]	254[2]	3590	2930	2610	1990	1130
Average	149	196	227	247[2]	254[2]	3980	3380	2990	2170	1350
MIX 1 : 3 BY VOLUME										
0	144	194	234	254[2]	254[2]	4670	4440	3900	3180	2060
5	151	201	237	254[2]	254[2]	4800	4280	3870	3050	1980
10	145	196	234	254[2]	254[2]	4780	4230	3650	3010	1780
20	144	190	230	254[2]	254[2]	4180	3730	3390	2740	1610
33	147	202	239	254[2]	254[2]	3820	3420	2910	2470	1490
Average	146	197	235	254[2]	254[2]	4450	4020	3540	2890	1780
MIX 1 : 2 BY VOLUME										
0	145	192	232	254[2]	254[2]	5480	5100	4720	4050	2910
5	150	197	234	254[2]	254[2]	5460	4980	4440	3840	2790
10	144	197	233	254[2]	254[2]	5260	4690	4290	3460	2610
20	148	194	233	254[2]	254[2]	4770	4140	3750	3090	2300
33	140	190	228	254[2]	254[2]	4240	3840	3350	2830	1910
Average	145	194	232	254[2]	254[2]	5040	4550	4110	3450	2500

[1]Average of 30 tests, 10 from each of 3 independent sets of tests in Groups 1, 3 and 4; 1860 average of 1790, 1880, 1900; 3270 average of 3250, 3240, 3330; and 2440 average of 2420, 2390, 2510. (Compare Table 32.)

[2]Exceeded diameter of flow table.

Table 28.—Comparison of Pebbles and Crushed Limestone.

(Data from Series 147)

Compression tests of 6 by 12-in. cylinders.
Mix 1 : 4 by volume. Relative consistency, 1.10.
Age at test, 28 days.
Cement: a mixture of 5 brands of portland cement purchased in Chicago.
Aggregate: Sand from Elgin, Ill., graded 0–No. 4 sieve. Pebbles from Elgin, Ill., graded No. 4–1½ in. Crushed Limestone from Chicago, graded No. 4–1½ in.
High-calcium hydrated lime was added to the materials in the batch; expressed as a percentage of the volume of cement.
Concrete for each specimen was mixed by hand in 1/5 cu. ft. batch.
The plasticity of the fresh concrete was measured by means of the "flow-table." (See Table 27.)
Specimens stored in moist room until day of test.
Each value is the average of 10 tests made on different days.

Hydrated Lime, Per Cent of Volume of Cement	"Flow" of Concrete						Compressive Strength, lb. per sq. in.					
	Pebbles			Crushed Limestone			Pebbles			Crushed Limestone		
	5.50[1]	5.75[1]	Av.	5.50[1]	5.75[1]	Av.	5.50[1]	5.75[1]	Av.	5.50[1]	5.75[1]	Av.
0	228	225[2]	224	200	190	195	3200	3220[2]	3210	3240	3180	3210
5	231	222[2]	226	206	193	200	3200	3200[2]	3200	3070	3020	3040
10	228	224[2]	226	209	195	202	2960	3090[2]	3020	2980	2950	2960
20	239	231[2]	235	215	202	208	2810	2760[2]	2780	2840	2690	2760
33	233	233[2]	233	216	201	208	2510	2610[2]	2560	2540	2540	2540
Average	232	227[2]	229	209	196	203	2940	2980[2]	2950	2930	2880	2900

[1]Fineness modulus of aggregate, 5.75, was derived by mixing 30 per cent of sand and 70 per cent of pebbles or crushed limestone by volume; for 5.50, the values were 37 and 63 per cent. See Table 26 for sieve analysis of aggregates.
[2]Same as values for 1 : 4 mix and relative consistency 1.10 in Table 27 (3220, average of 30 tests).

Table 29.—Comparison of Hydrated Lime and Portland Cement as "Admixtures."

Compression tests of 6 by 12-in. cylinders.
Age at test, 28 days.
Cement: a mixture of 5 brands of portland cement purchased in Chicago.
Aggregate: sand and pebbles from Elgin, Ill., graded 0–1½ in.
High-calcium hydrated lime was added to the materials in the batch; expressed as a percentage of the volume of cement.
Concrete for each specimen was mixed by hand in 1/5 cu. ft. batch.
The plasticity of the fresh concrete was measured by means of the "flow-table." (See Table 24.)
Specimens stored in moist room until day of test.
Each value is the average of 10 tests made on different days.

Admixture Per Cent of Volume of Cement	"Flow" of Concrete						Compressive Strength, lb. per sq. in.					
	Mix 1 : 5		Mix 1 : 4		Average		Mix 1 : 5		Mix 1 : 4		Average	
	Hydrated Lime	Cement	Hydrated Lime	Cement	Hydrated Lime	Cement	Hydrated Lime	Cement	Hydrated Lime	Cement	Hydrated Lime	Cement
Group 3. Mixing Water Constant for Each Mix, "Flow" Variable. Concrete Without Admixture of Relative Consistency 1.25												
0	233	232	245	245	239	239	1000	1880	2510	2390	2210	2140
	(232)[1]		(244)[1]		(238)		(1890)[1]		(2440)[1]		(2160)	
1	235	230	239	242	237	236	1960	1950	2440	2520	2200	2240
2	231	227	238	240	234	234	1980	1990	2520	2610	2250	2300
5	232	230	237	240	234	235	1930	2060	2570	2770	2250	2410
10	229	237	231	232	230	234	2030	2410	2620	3100	2320	2750
20	231	229	229	233	230	231	2190	2790	2740	3500	2460	3140
33	220	223	212	216	216	220	2240	3410	2810	4080	2520	3740
Group 4. Mixing Water Increased with Admixture to Produce Constant "Flow." Concrete Without Admixture of Relative Consistency 1.10												
0	....	....	230	225	....	....	....	....	3180	3240	....	....
			(225)[1]						(3220)[1]			
1	....	....	229	226	....	....	....	....	3310	3280	....	....
2	....	....	229	229	....	....	....	....	3120	3130	....	....
5	....	....	231	222	....	....	....	....	3130	3540	....	....
10	....	....	231	218	....	....	....	....	3060	3510	....	....
20	....	....	226	224	....	....	....	....	2950	3830	....	....
33	....	....	222	218	....	....	....	....	2840	4290	....	....
		Aver.	228	223					3090	3540		

[1]Average of 30 tests, 10 each from the two independent sets of tests in the line above (without hydrated lime or additional cement), and 10 tests from the corresponding mixes in Group 1.

TABLE 30.—REDUCTION IN STRENGTH OF CONCRETE BY HYDRATED LIME.

Compression tests of 6 by 12-in. cylinders at age of 28 days.
Changes in strength are percentages for each 1 per cent addition of hydrated lime (by volume of cement).
The values were determined from the curves in Fig. 16 to 18.

Relative Consistency	Kind of Aggregate	Fineness Modulus of Aggregate	Reduction in Strength					
			1 : 6	1 : 5	1 : 4	1 : 3	1 : 2	Average
GROUP 1. MIXING WATER INCREASED IN PROPORTION TO QUANTITY OF HYDRATED LIME AND ITS NORMAL CONSISTENCY								
.90	Sand and pebbles	5.75	0.40	0.39	0.63	0.75	0.74	0.58
1.00	" " "	5.75	0.47	0.47	0.59	0.80	0.91	0.65
1.10	" " "	5.75	0.77	0.48	0.71	0.80	0.91	0.73
1.25	" " "	5.75	0.60	0.48	0.84	0.75	0.98	0.73
1.50	" " "	5.75	1.00	0.47	0.87	0.91	0.98	0.85
		Average	0.65	0.46	0.72	0.80	0.90	0.71
GROUP 2. MIXING WATER INCREASED IN PROPORTION TO QUANTITY OF HYDRATED LIME AND ITS NORMAL CONSISTENCY								
1.10	Sand and pebbles	5.50	....	....	0.62	....	....	0.62
"	" " "	5.75	....	....	0.62	....	....	0.62
"	Sand and crushed limestone	5.50	....	....	0.62	....	....	0.62
"	" " " "	5.75	....	....	0.62	....	....	0.62
		Average			0.62			0.62
GROUP 3. MIXING WATER CONSTANT FOR ALL PERCENTAGES OF HYDRATED LIME; "FLOW" VARIABLE								
1.25*a*	Sand and pebbles	5.75	....	+0.66*b*	+0.57*b*	....	....	+0.61
GROUP 4. MIXING WATER INCREASED WITH QUANTITY OF ADMIXTURE TO OBTAIN A CONSTANT "FLOW"								
1.10*c*	Sand and pebbles	5.75	....	....	0.34*d*	....	....	0.34

+Represents an increase in strength.

a Relative consistency of mix containing no hydrated lime was 1.25. As hydrated lime was added the mix became drier, or about 1.05 relative consistency for 33 per cent hydrated lime. It would be expected that hydrated lime would increase the strength of concrete under these conditions.

b The addition of portland cement increased the strength of the concrete by 2.58 per cent and 2.25 per cent respectively. The "flow" was affected alike by hydrated lime and cement.

c Water calculated for concrete without hydrated lime. With the addition of hydrated lime sufficient water was added to keep "flow" approximately constant.

d Addition of cement in a like manner gave an increase of 1.00 per cent.

TABLE 31.—REDUCTION IN STRENGTH OF CONCRETE DUE TO CERTAIN PERCENTAGES OF HYDRATED LIME.

Based on compression tests of 6 by 12-in. cylinders at age of 28 days in Group 1; computed from slopes of inclined dotted lines in Fig. 16.

Mix by Volume	Hydrated Lime			Reduction in Strength of Concrete, per cent.					
	Per Cent of Volume of		Per Cent of Weight of Cement	0.90[1]	1.00[1]	1.10[1]	1.25[1]	1.50[1]	Average
	Aggregate	Cement							
1 : 6	5	30	12.8	10.7	13.5	14.2	21.0	30.6	18.0
1 : 5		25	11.6	5.8	6.2	9.0	15.8	13.6	10.1
1 : 4		20	8.5	7.4	9.4	15.6	23.0	25.8	16.2
1 : 3		15	6.4	4.1	10.4	9.8	9.4	17.7	10.3
1 : 2		10	4.2	4.0	8.0	9.1	14.6	10.3	9.2
			Average	6.4	9.5	11.5	16.8	19.6	12.8
1 : 6	4	24	10.2	8.0	10.6	8.7	18.1	23.5	13.8
1 : 5		20	8.5	6.3	3.8	6.1	12.9	12.7	8.4
1 : 4		16	6.9	3.4	6.6	11.6	13.1	20.2	11.0
1 : 3		12	5.1	0.2	7.0	7.7	6.9	15.0	7.4
1 : 2		8	3.4	2.6	5.9	7.8	10.9	7.9	7.0
			Average	4.1	6.8	8.4	12.4	15.9	9.5
1 : 6	3	18	7.7	5.3	7.5	3.5	16.1	17.3	9.9
1 : 5		15	6.4	2.6	1.9	4.7	11.8	8.6	5.9
1 : 4		12	5.2	+0.5	3.6	7.6	9.8	14.7	7.0
1 : 3		9	3.8	+2.4	4.5	5.4	5.0	11.2	4.7
1 : 2		6	2.5	1.1	3.5	6.6	7.2	5.5	4.8
			Average	1.2	4.2	5.6	10.0	11.5	6.5

[1] Relative consistency of concrete.

+ Represents an increase in strength.

TABLE 32.—VARIATION IN PARALLEL SETS OF TESTS.

Aggregate: sand and pebbles, fineness modulus 5.75.

Concrete strength is given in pounds per square inch.

Groups	Mix by Volume	Relative Consistency	Hydrated Lime, per cent	Strength as Determined by Duplicate Sets of 10 Tests				Flow as Determined by Duplicate Sets of 10 Tests		
				First Set	Second Set	Difference	Per Cent	First Set	Second Set	Difference[1]
1 and 3	1 : 5	1.25	0	1790	1880	90	4.90	230	232	2
1 and 3	1 : 5	1.25	0	1790	1900	110	5.96	230	230	0
3	1 : 5	1.25	0	1880	1900	20	1.06	232	230	2
1 and 4	1 : 4	1.10	0	3250	3240	10	0.31	221	225	4
1 and 4	1 : 4	1.10	0	3250	3330	80	2.43	221	230	9
4	1 : 4	1.10	0	3240	3330	90	2.74	225	230	5
1 and 3	1 : 4	1.25	0	2420	2390	30	1.24	242	245	3
1 and 3	1 : 4	1.25	0	2420	2510	90	3.65	242	245	3
3	1 : 4	1.25	0	2390	2510	120	4.90	245	245	0
3 and 4	1 : 4	1.10	33	2810	2840	30	1.06	212	222	10
						Average	2.82			3.8

[1] Differences are also percentages based on the original base diameter of the truncated cone, "flow" = 100

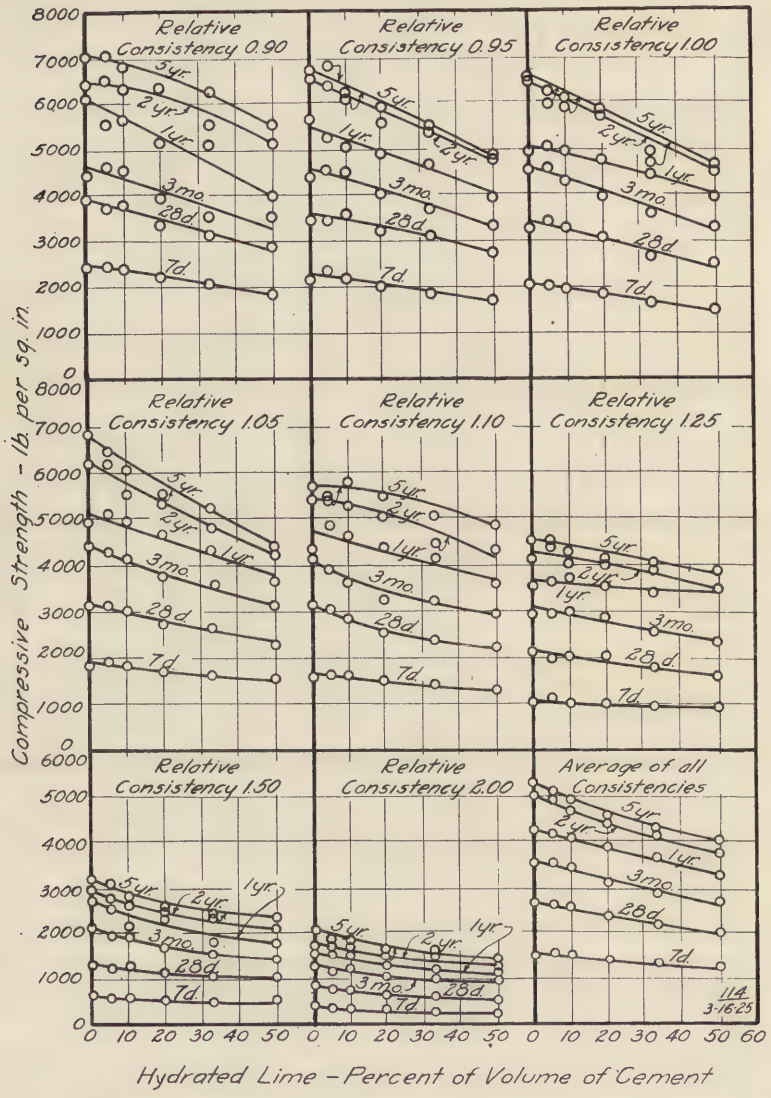


FIG. 1.—Effect of Hydrated Lime on the Strength of Concrete.
(Different Consistencies and Ages—Series 114.)

Compression tests of 6 by 12-in. concrete cylinders.
Mix, 1:4 by volume.
Sand and pebble aggregate, graded 0-1½ in., fineness modulus, 5.75.
Specimens stored in damp sand; tested damp.
Each value is the average of five tests made on different days.
Compare Fig. 2 to 5.

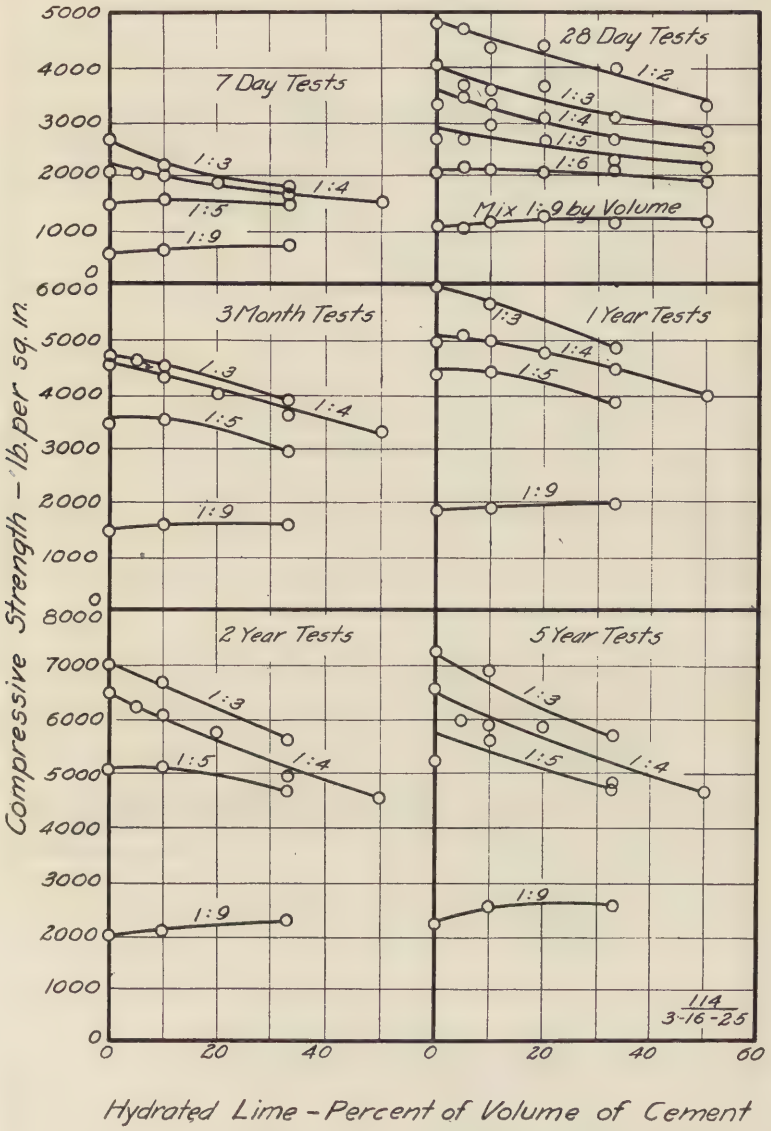


FIG. 2.—Effect of Hydrated Lime on the Strength of Concrete.
(Different Mixes and Ages—Series 114.)

Compression tests of 6 by 12-in. concrete cylinders.
Relative consistency of concrete, 1.00.
Sand and pebble aggregate, graded 0-1½ in., fineness modulus, 5.75.
Specimens stored in damp sand; tested damp.
Each value is the average of five tests made on different days.
Compare Fig. 1, 3, 4 and 5.

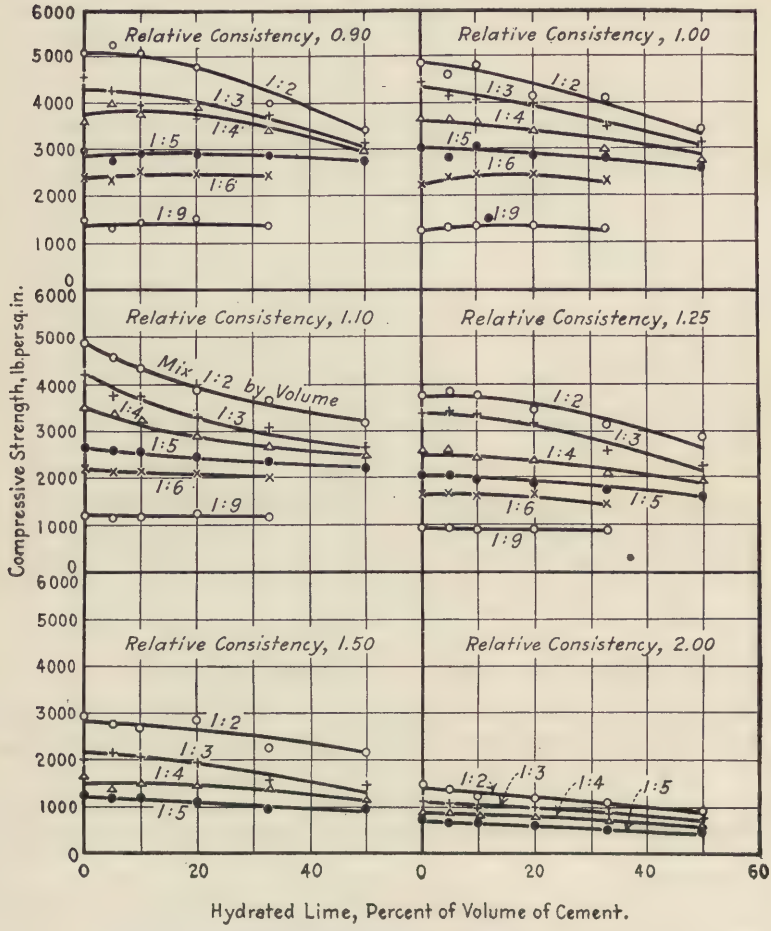


FIG. 3.—Effect of Hydrated Lime on the Strength of Concrete.
(Different Mixes and Consistencies—Series 130.)

Compression tests of 6 by 12-in. concrete cylinders. Data from Table 4.
Sand and pebble aggregate, graded 0-1½ in., fineness modulus, 5.75.
Specimens stored in damp sand; tested damp at age of 28 days.
Each value is the average of five tests made on different days.
Compare Fig. 1, 2, 4 and 5.

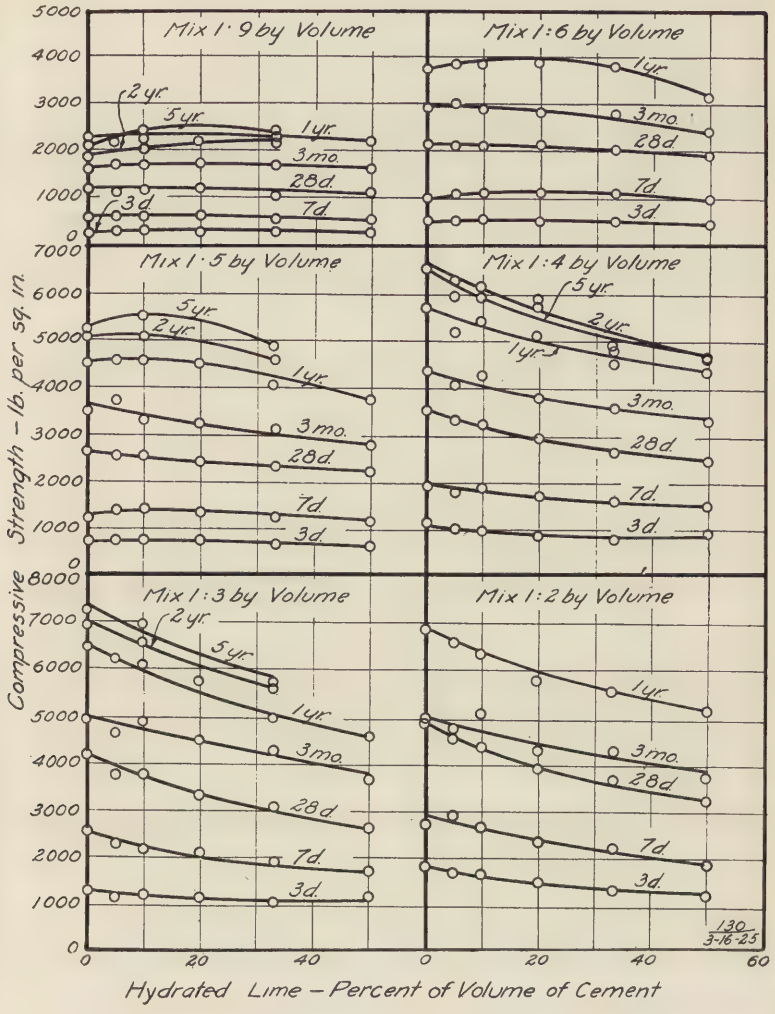


FIG. 4.—Effect of Hydrated Lime on the Strength of Concrete.
(Different Mixes and Ages—Series 130.)

Compression tests of 6 by 12-in. concrete cylinders. Data from Table 5.
Mix by volume.
Sand and pebble aggregate, graded 0-1½ in., fineness modulus, 5.75.
Specimens stored in damp sand; tested damp.
Each value is the average of five tests made on different days.
Compare Fig. 1 to 3 and 5.

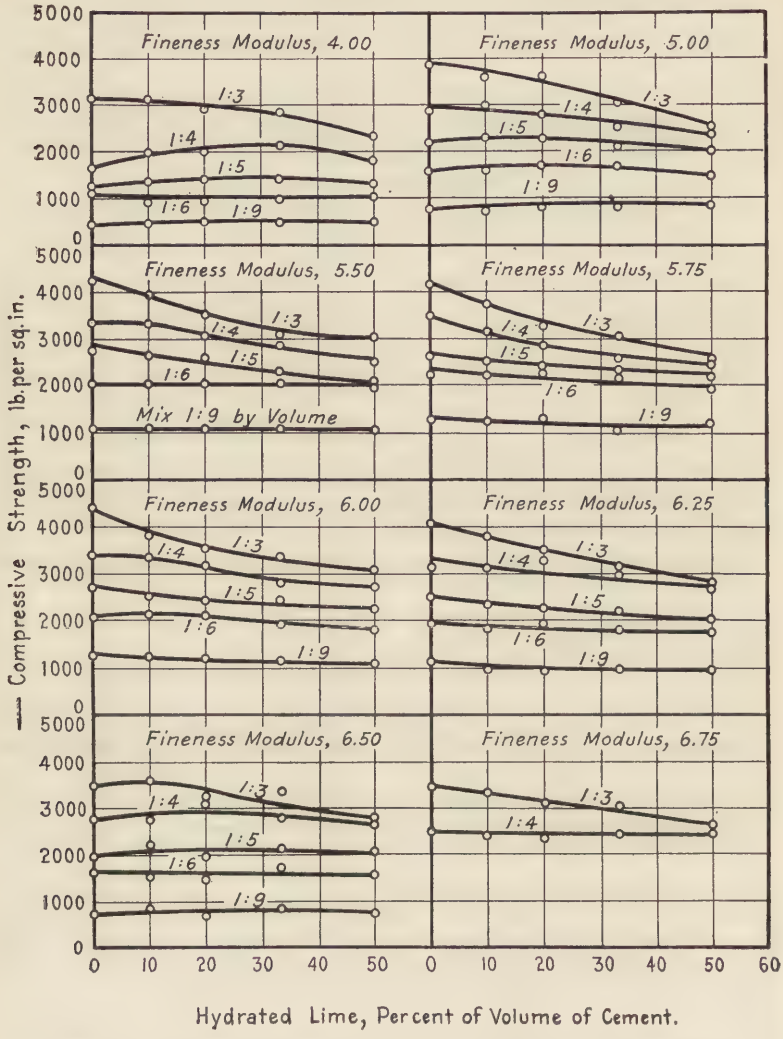


FIG. 5.—Effect of Hydrated Lime on the Strength of Concrete.
(Different Gradings of Aggregates and Mixes—Series 130.)

Compression tests of 6 by 12-in. concrete cylinders. Data from Table 6.

Specimens stored in damp sand; tested damp at age of 28 days.

Sand and pebble aggregate, graded 0-1½ in. Different values of fineness modulus were derived by combining sand and pebbles in different proportions. Values for fineness modulus 5.50 to 6.00, represent the usual range for aggregates of this size. For sieve analysis see Table 2.

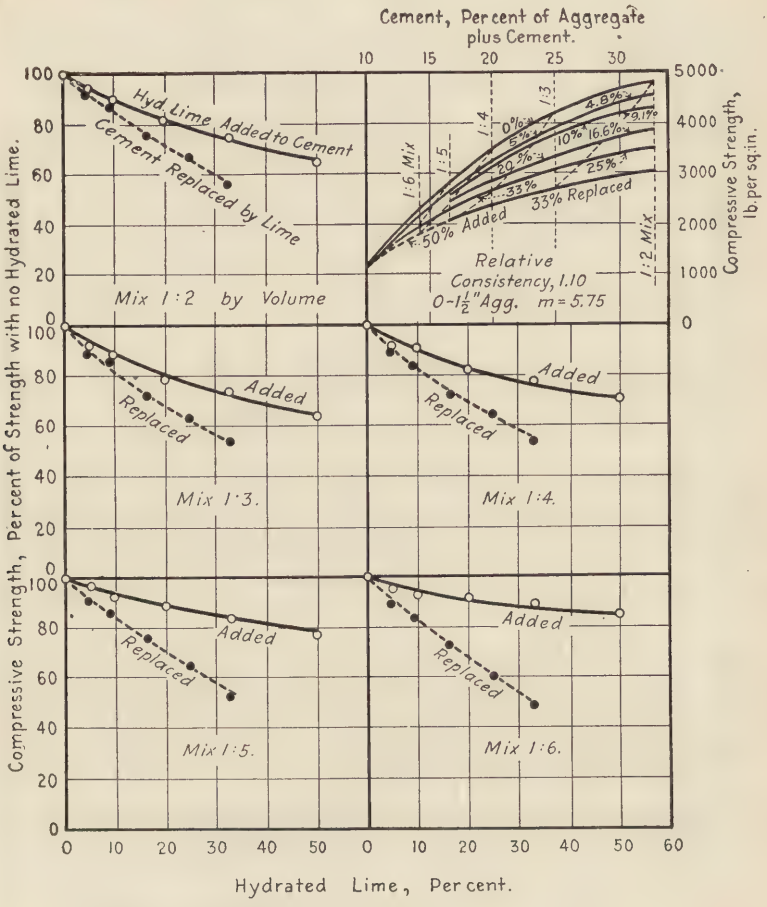


FIG. 6.—Effect of Hydrated Lime on the Strength of Concrete.

Compression tests of 6 by 12-in. cylinders at age of 28 days.

Aggregate, sand and pebbles from Elgin, Ill., graded 0-1½ in., fineness modulus, 5.75.

Specimens stored in damp sand; tested damp.

In the upper right corner the relation between the strength of concrete and the quantity of cement is platted for different percentages of hydrated lime. In the tests hydrated lime was added to the cement; however, the effect of replacing cement by hydrated lime is also indicated. The intersections of the vertical dotted curves with the solid curves give the strengths of concrete when hydrated lime was added and the diagonal dotted lines give the strengths of concrete when the cement was replaced by hydrated lime.

The other diagrams in this figure show the relative strength of concrete of different mixtures, both where hydrated lime was added to the cement in the batch, and where the hydrated lime replaced cement.

Based on tests in Table 4.

Compare Fig. 11 and 12.

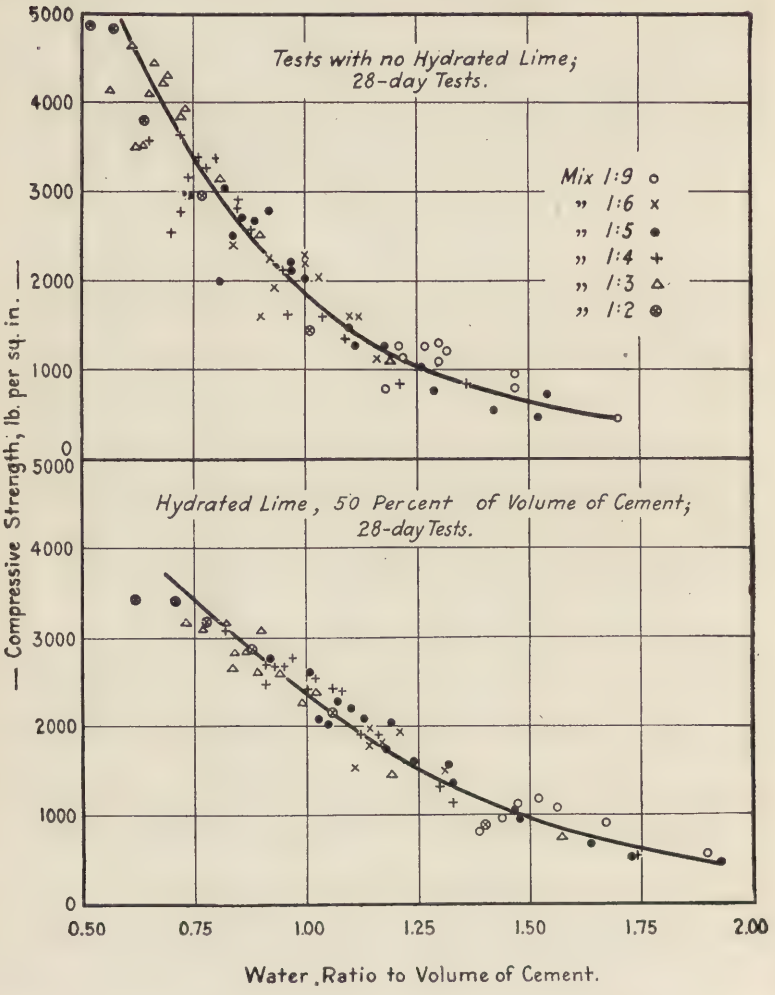


FIG. 7.—Water-Ratio-Strength Relation for Concrete With and Without Hydrated Lime.
(Series 130.)

Compression tests of 6 by 12-in. cylinders. Data from Tables 4 to 7.
Specimens stored in damp sand; tested damp at age of 28 days.

In platting these curves all water except that absorbed by the aggregate was accredited to the cement; that is, the water absorbed by the hydrated lime was not deducted in calculating the water-ratio. For example, the water-ratio for a 1 : 4 mix (relative consistency, 1.10, with aggregate of fineness modulus, 5.75), without hydrated lime is 0.78; with 50 per cent hydrated lime it is 1.00. The strength in the first instance is 3100 lb. per sq. in., while with 50 per cent hydrated lime it is 2400 lb. per sq. in. These curves bring out the water-ratio-strength relation for a given condition, but do not show directly the effect of hydrated lime on the strength of concrete.

Similar curves may be drawn for other percentages of hydrated lime.

Compare Fig. 10.

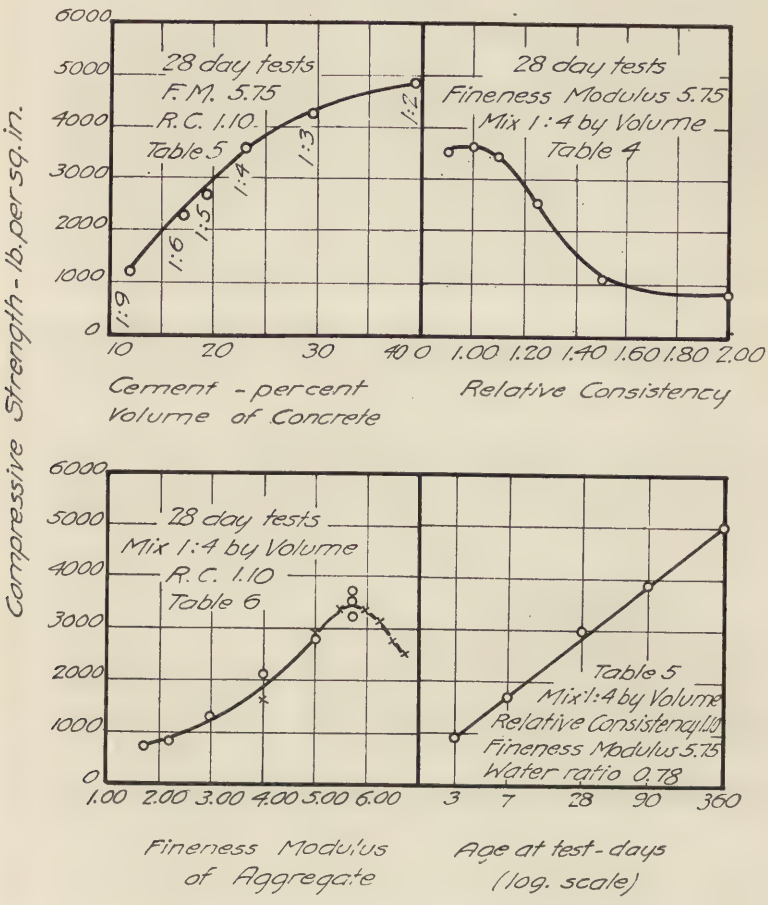


FIG. 8.—Typical Concrete Strength Relations.
(Series 130.)

Compression tests of 6 by 12-in. cylinders. Mix by volume.
Sand and pebble aggregate.
Specimens stored in damp sand; tested damp.
Each value is the average of five or more tests made on different days.
Data from Tables 4 to 6.

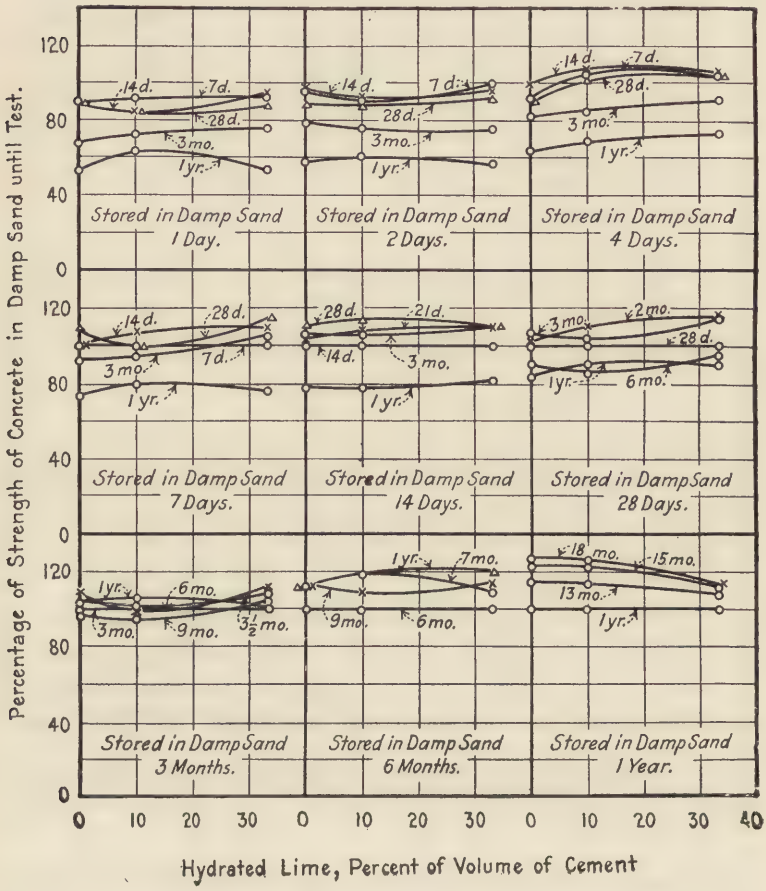


FIG. 9.—Effect of Hydrated Lime on the Strength of Concrete Cured under Different Conditions.
(Series 114.)

Values expressed as percentages of strength of concrete stored in damp sand until tested. Specimens stored in damp sand for periods indicated; remainder of time in air until tested at ages noted on curves.

Compression tests of 6 by 12-in. cylinders. Mix, 1 : 4 by volume.

Sand and pebble aggregate, graded 0-1½ in., fineness modulus, 5.75.

Relative consistency of concrete, 1.00.

Each value is the average of five tests made on different days.

One and five-year tests not platted.

Data from Table 9.

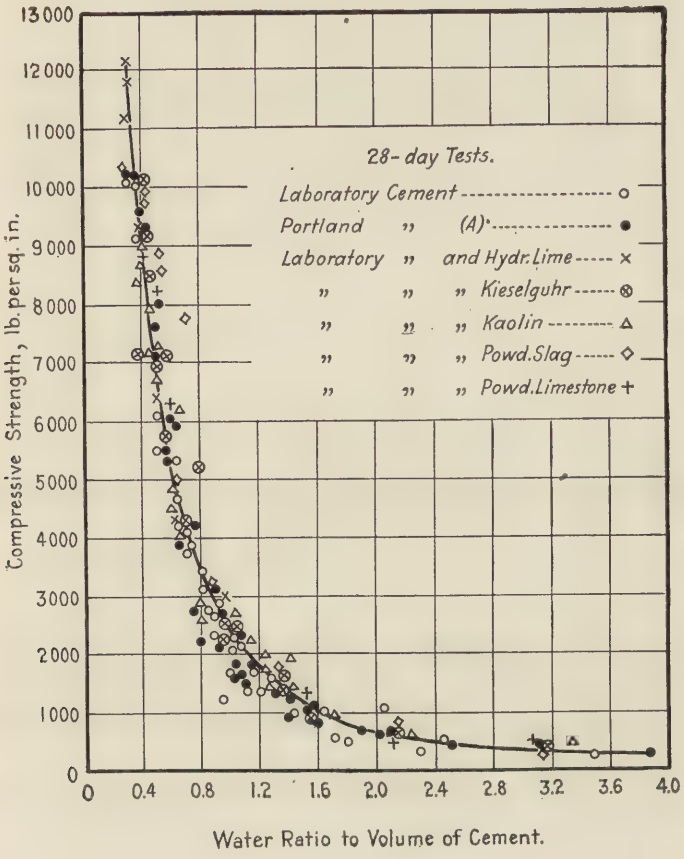


FIG. 10.—Effect of Water on the Strength of Mortar.
(Series 100.)

Compression tests of 2 by 4-in. cylinders, neat and 1:3 mixes.
Specimens stored in water; tested damp at age of 28 days.
Details of these tests are not reported. Similar data are on hand from tests at 7 days, 3 months and 1 year. Compare Fig. 7.

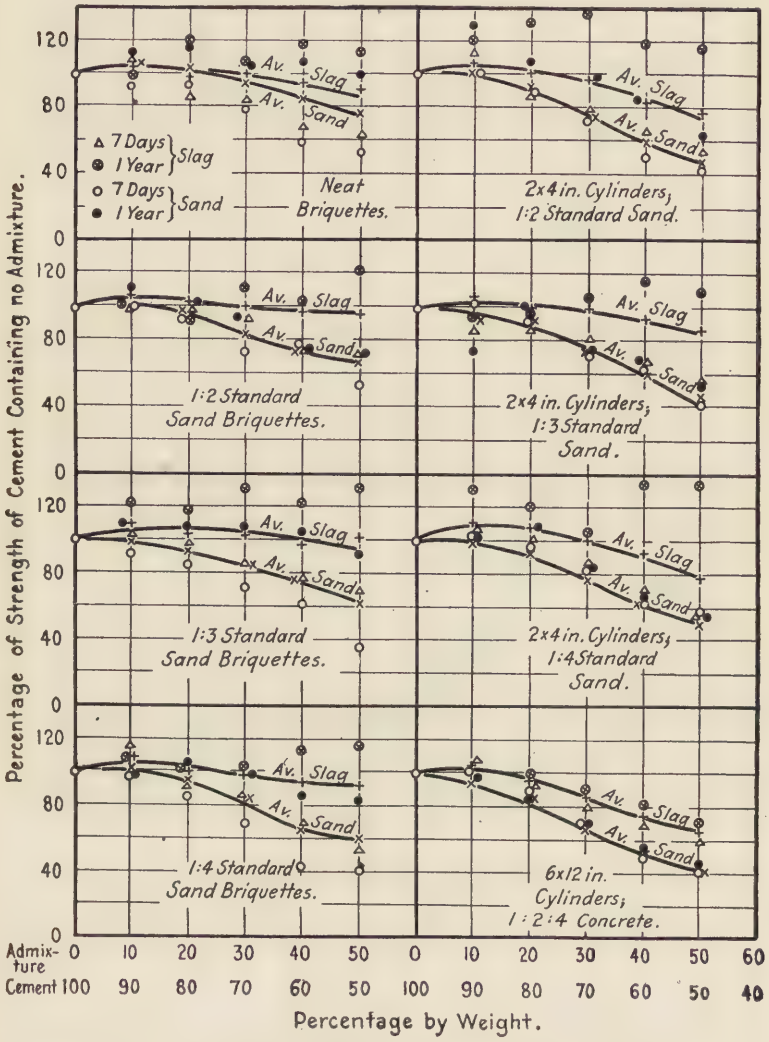


FIG. 11.—Relative Strengths of Sand and Slag Cements.
(Series 58.)

Values are expressed as percentages of the strength of mortar or concrete using portland cement without admixture.

Sand or slag was added to the cement prior to final grinding.

For mortar strength and miscellaneous tests of sand and slag cements, see Table 1.

Mortar specimens stored in water; tested wet.

Concrete specimens stored in damp sand; tested damp.

Points shown for 7-day and 1-year tests only. The average is from 7-day, 28-day, 3-month, 6-month and 1-year tests.

Each value is the average of four tests made on different days.

Further details of these tests are not reported.

Compare Fig. 6 and 12.

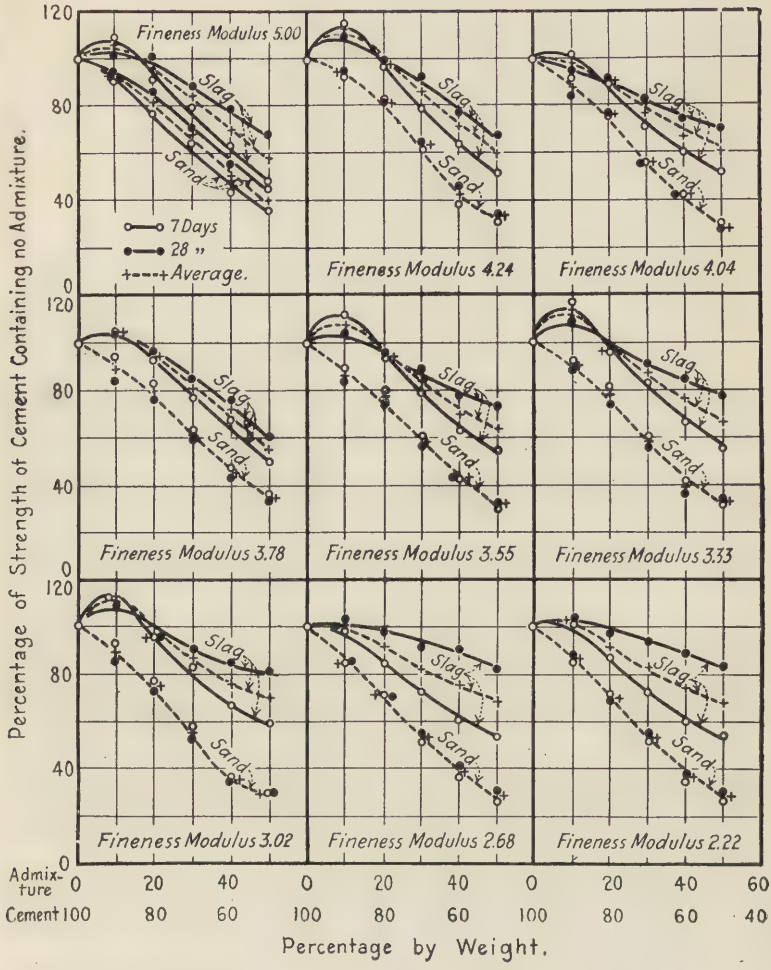


FIG. 12.—Relative Strengths of Sand and Slag Cements.
(Series 59.)

Values expressed as percentages of strength of mortar or concrete using portland cement without admixture.

Sand or slag was added to the cement prior to final grinding.

For mortar strength and miscellaneous tests of sand and slag cements, see Table 1.

For grading of aggregates see Table 2. The fineness modulus of the aggregate was varied by causing the grading to conform to certain predetermined smooth sieve and analysis curves.

Specimens stored in water; tested wet.

Each value is the average of 6 to 8 tests made on 3 or 4 different days.

Further details of these tests are not reported.

Compare Fig. 6 and 11.

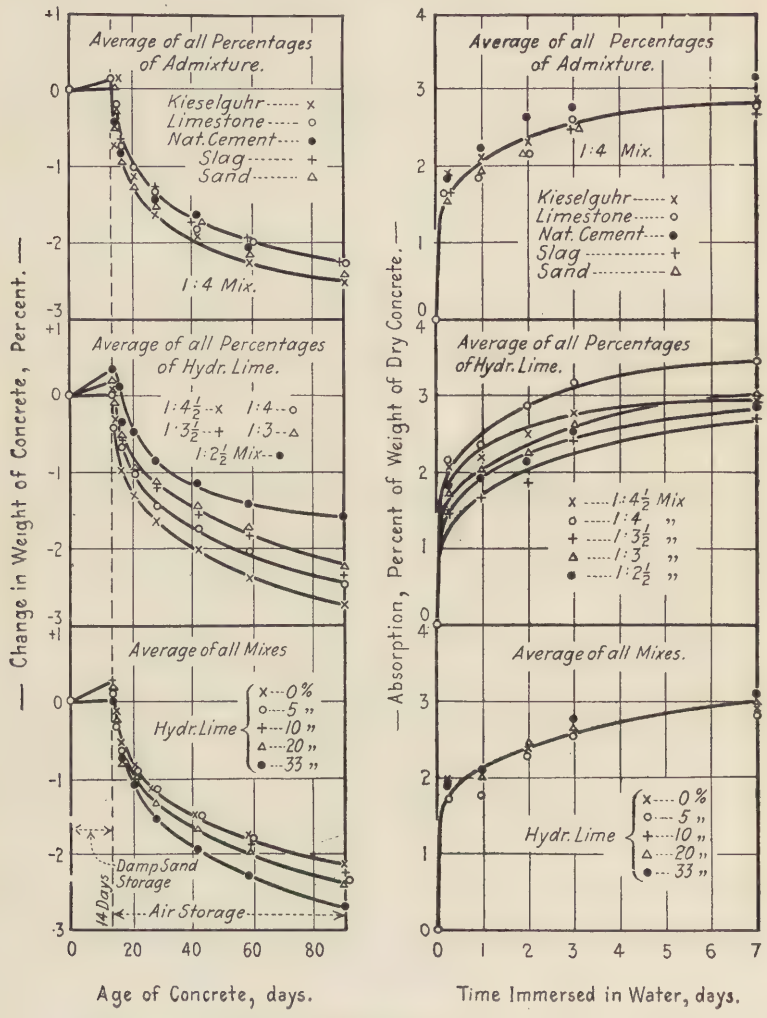


FIG. 13.—Effect of Powdered Admixtures in Concrete on the Evaporation and Absorption of Water.
(Series 130.)

Tests made on 8 by 8 by 5in. wear blocks; evaporation tests were made during the period of air storage in the laboratory, following 14 days in damp sand. Absorption tests were made on the same blocks, subsequent to the wear test, at the age of about 6 months.

Each value for evaporation is the average of 75 tests made in sets of 5 on 3 different days.

Each value for absorption is the average of 10 to 25 tests.

See Tables 20 and 21 for results of wear tests.

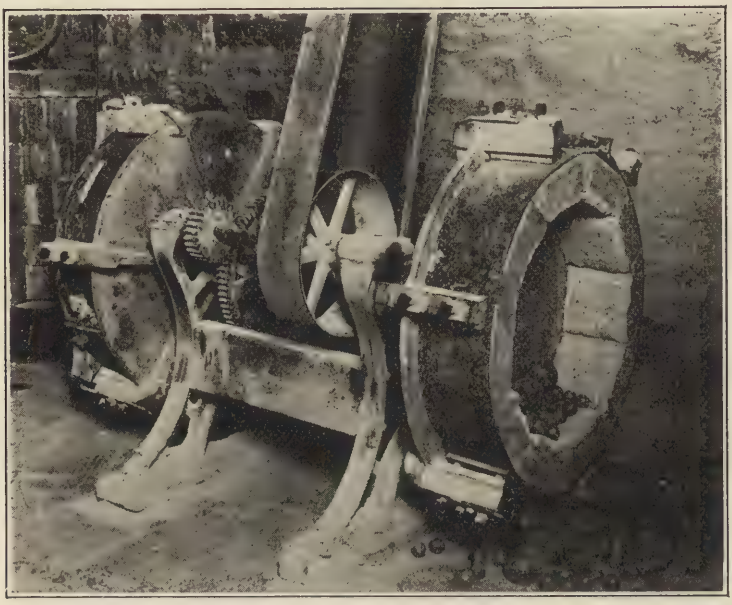


FIG. 14.—Talbot-Jones Rattler for Wear Tests of Concrete.

Wear tests were made on 8 by 8 by 5-in. concrete blocks, after storage for 2 weeks in damp sand and 10 weeks in air.

Test consists of 1800 revolutions of the head at 30 r. p. m., using 200 lb. of cast-iron balls; 10 balls, 3¾ in. in diameter and about 140 balls, 1⅞ in. in diameter.

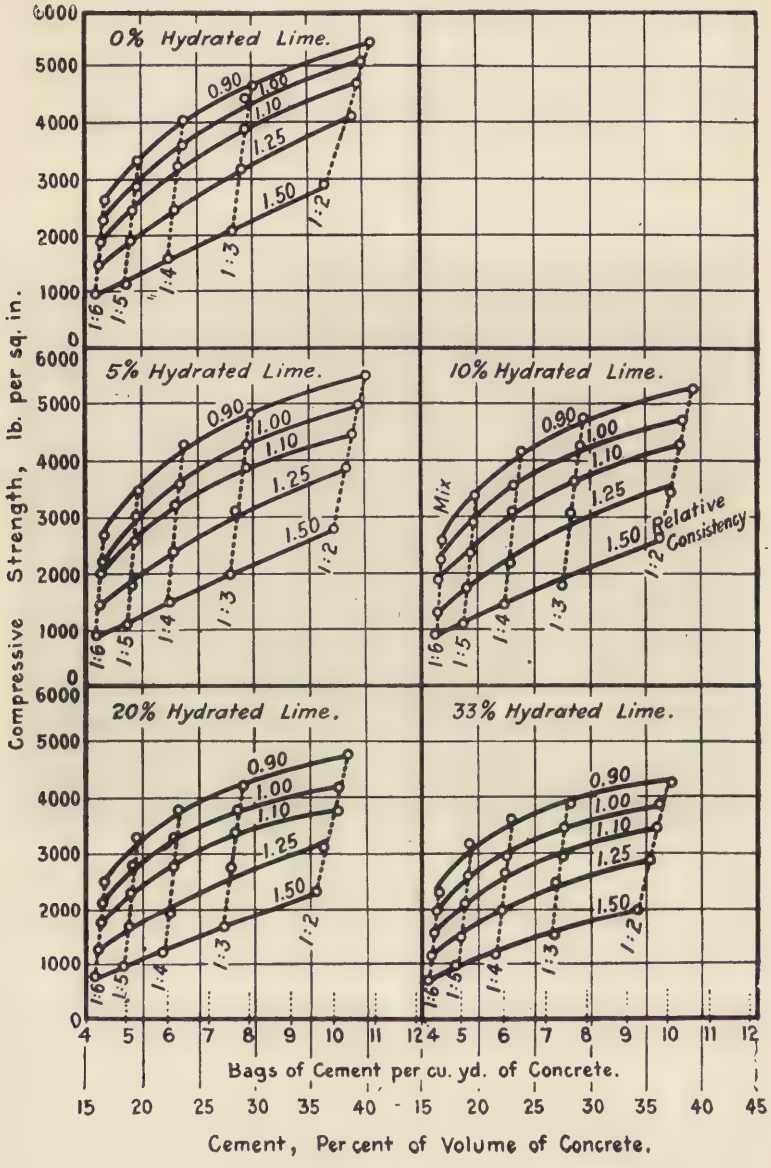


FIG. 15.—Effect of Quantity of Cement on the Strength of Concrete.

Compression tests of 6 by 12-in. cylinders at 28 days. Data from Group 1. (Table 27.)

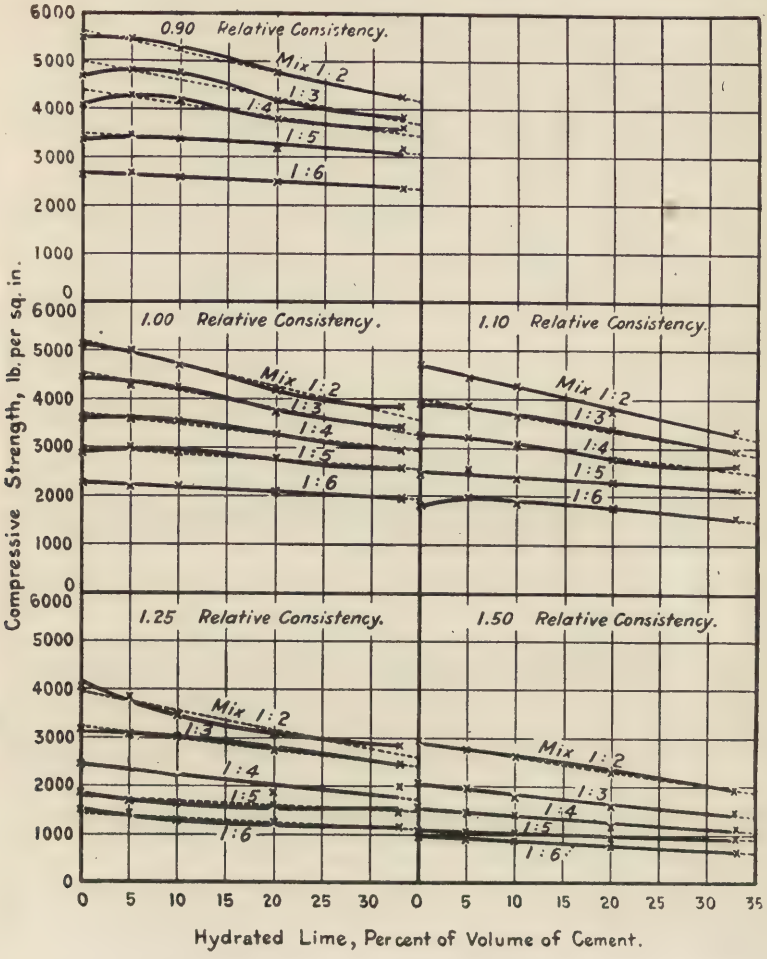


FIG. 16.—Effect of Hydrated Lime on the Strength of Concrete.

Compression tests of 6 by 12-in. cylinders at 28 days. Data from Group 1. (Table 27.)

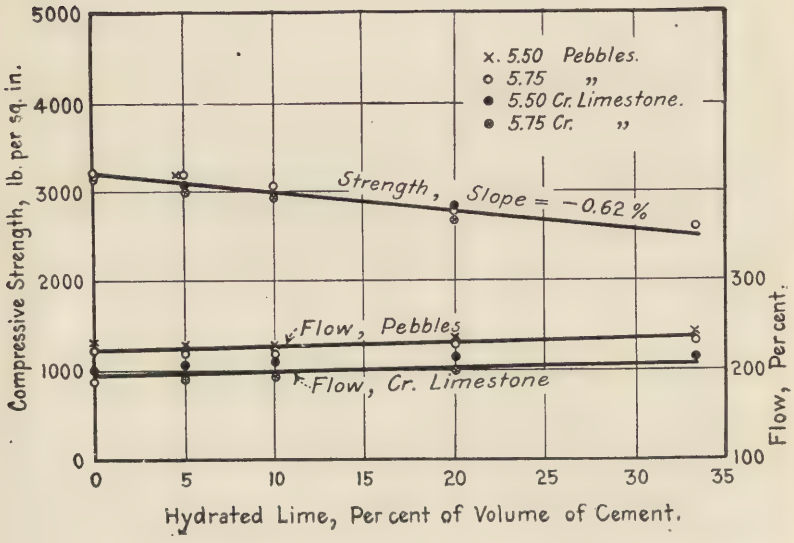


FIG. 17.—Effect of Hydrated Lime on the Strength of Concrete.

Compression tests of 6 by 12-in. cylinders at 28 days. Data from Group 2. (Table 28.)

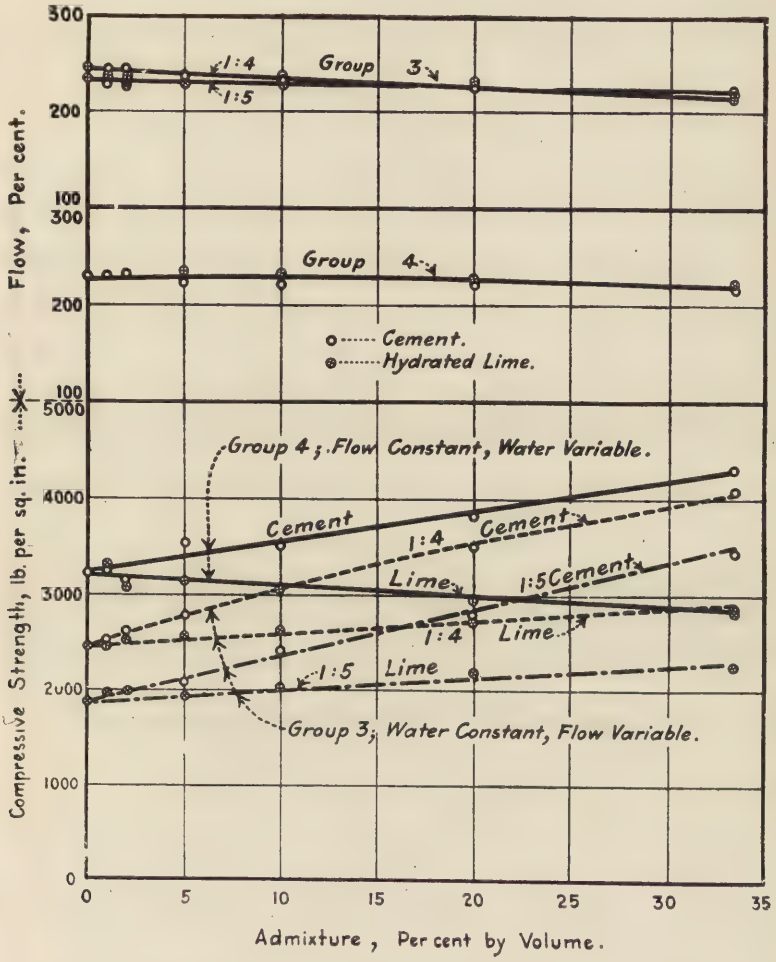


FIG. 18.—Effect of Hydrated Lime on the Strength of Concrete.

Compression tests of 6 by 12-in. cylinders at 28 days. Data from Group 3. (Table 29.)

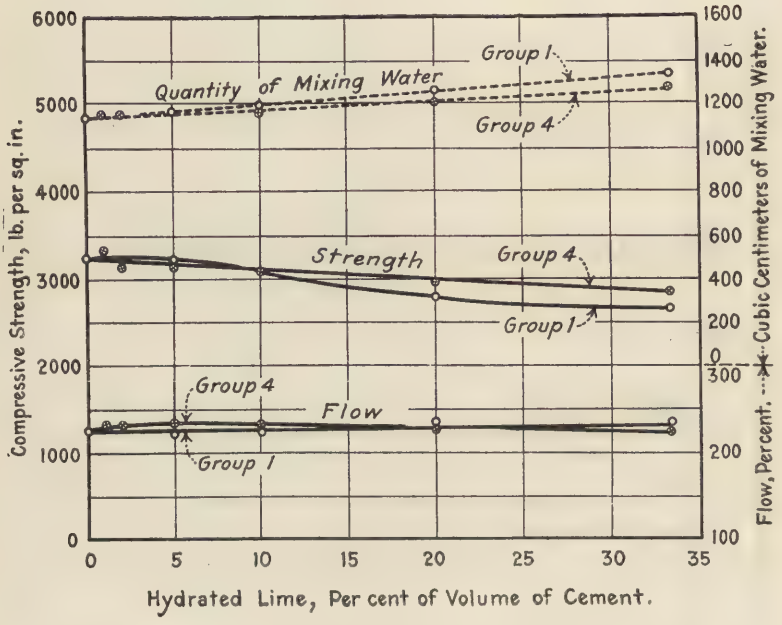


FIG. 19.—Effect of Hydrated Lime on the Strength of Concrete.

Compression tests of 6 by 12-in. cylinders at 28 days. Data from Groups 1 and 4. (Tables 27 and 29.)

Bulletin 9

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Quantities of Materials for Concrete

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FOREWORD

The first edition of this Bulletin was published in November, 1921. In this second edition the text has been rewritten and rearranged, although no fundamental changes in treatment have been made. The principal changes are:

(1) The addition of Fig. 1, the water-ratio-strength relation for concrete which forms the basis of the tables.

(2) Statement of the quantity of mixing water which forms the basis of the tables of proportions.

(3) Tables for 1500-lb. concrete have been omitted; concrete of this quality is seldom required.

(4) References to literature have been revised.

(5) Examples are given of:

(a) Conversion of quantity of aggregates measured dry and rodded, into terms of field measurements.

(b) Estimation of proportions for aggregate sizes, concrete strengths and slumps not given in the tables.

(6) Descriptions of test methods have been enlarged and revised to bring them into line with recent changes in A.S.T.M. Standards; see Appendix 1.

(7) A brief discussion of "Field Tests of Concrete," has been added as Appendix 2.

No changes have been made in the proportions and quantities in the tables.

QUANTITIES OF MATERIALS FOR CONCRETE

By Duff A. Abrams and Stanton Walker

Introduction

Concrete is a suitable mixture of cement, water, and inert materials called aggregate, which when allowed to set and harden produces a rock-like mass. The selection of the proportions in which the ingredients shall be used constitutes one of the most important phases of the manufacture of concrete.

In the past it has been customary to combine fine and coarse aggregates in more or less arbitrary ratios. The quality of the concrete was assumed to be governed solely by the quantity of cement used. The method of specifying different quantities of cement was by proportions of cement, fine and coarse aggregates such as 1:2:4, etc. It appears that these proportions were based on a consideration of the voids in the coarse aggregate, it being assumed that 2 volumes of sand would somewhat more than fill the voids in 4 volumes of coarse aggregate. Little or no attention was given to the quantity of mixing water, size and grading of the aggregate, curing of the concrete, and other factors which are now known to be of utmost importance. The effect of these variables was generally obscured by lack of proper testing technique.

During the past 15 years considerable attention has been given to the testing of concrete. As a result, a large amount of information on the effect of these factors on the strength of concrete is now available, which enables us to state with considerable accuracy the combinations required for different gradings of aggregate for concrete of a specified strength.

The tables of proportions and quantities forming the principal subject matter of this Bulletin constitute a resumé of a large number of experimental investigations which have been carried out at the Structural Materials Research Laboratory through the cooperation of the Portland Cement Association and Lewis Institute. These investigations, made during the past 10 years, include about 150,000 tests on the strength and yield of concrete produced under standardized conditions for wide variations in the proportions of constituent mate-

rials, and different methods of manipulation, curing conditions, etc. These tests fall in the following categories:

1. Standardization of test methods,
2. Effect of grading of aggregates,
3. Effect of quantity of mixing water,
4. Effect of quantity of cement,
5. Relative merits of different types of aggregates,
6. Comparison of concrete and mortar tests,
7. Effect of curing conditions,
8. Effect of age of concrete,
9. Effect of admixtures in concrete,
10. Studies of time of mixing,
11. Methods of measuring plasticity or workability of concrete,
12. Comparisons of compressive strength, flexure, wear, yield and absorption of concrete.

Part of the data of the above mentioned tests furnished the subject matter of our Bulletin 1, "Design of Concrete Mixtures," published in 1918, in which the water-ratio method of proportioning concrete was first described.

The first of our tables of proportions and quantities was published in 1920 under the title "Table of Proportions and Quantities for Concrete for Road Construction."[1] The above-mentioned table was intended solely for use in concrete road construction, hence an excess of fine aggregate was used to facilitate hand finishing. Experience has shown that with more recent mechanical methods of finishing concrete roads, it is not necessary to "over-sand" the mix to the extent that was formerly practiced. The tables in this Bulletin are based on more complete data than were available when the first table was prepared.

Tables are given below for concrete of compressive strengths of 2000, 2500, 3000, 3500, and 4000 lb. per sq. in. at 28 days using fine and coarse aggregates of different sizes and concrete of a wide range of workability as measured by the slump test.

The same tables were published in the Report of the Committee on Masonry of the American Railway Engineering Association,[2] in the Report of the Joint Committee on Standard Specifications for Concrete and Reinforced Concrete,[3] and elsewhere.

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[1]Concrete Highway Magazine, May, 1920; Eng. News-Rec., May 13, 1920; Proc. Am Soc. Testing Mat., v. 20, Part I, 1920; Canadian Engineer, June 17, 1920.

[2]Bull. 242, Am. Railway Eng. Assn., December, 1921.

[3]Proc. Am. Soc. Testing Mat., v. 24, Part I, 1924; Proc. Am. Soc. Civil Eng., October, 1924; Proc. Am. Concrete Inst., 1925.

EARLIER TABLES OF QUANTITIES

These tables differ principally from the tables by Thacher[4] and Taylor and Thompson[5] in three respects:

a. The quantity of mixing water and workability of the concrete have been stated. The fundamental importance of these factors was not appreciated at the time the earlier tables were published.

b. Quantities are based on volumes of aggregate measured *dry* and *rodded*. The older tables apparently were based on volumes of materials measured damp and loose under field conditions. A given quantity of sand measured damp and loose may occupy as much as 30% more volume than the same quantity measured dry and rodded.

c. Proportions have been selected which will produce concrete of definite strengths; the older tables gave quantities of materials for certain arbitrary mixtures (such as 1:2:4) presumably based on the assumption that the quantity of cement alone governed the strength.

WATER-RATIO METHOD OF PROPORTIONING CONCRETE

One of the most important results of the experimental studies of concrete made in this Laboratory was the water-ratio method of proportioning concrete. This method is based on the dependence of strength upon the ratio of volume of mixing water to volume of cement (water-ratio). Our tests have shown that for given conditions of curing, temperature, etc., the strength of concrete is fixed by the water-ratio, *so long as the concrete is workable* and the *aggregates are clean and structurally sound.* The size and grading of the aggregate, the quantity of cement and the consistency of the concrete affect the strength only in so far as they influence the quantity of mixing water required to give concrete of the necessary workability.

The significance of this important relation is more readily appreciated when the cement paste is thought of as a glue binding the aggregates together. Too much mixing water dilutes the glue and hence reduces its strength.

These investigations have shown that the inter-relation of strength and proportions of materials in concrete may be expressed by the following principles:

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[4] "Materials of Construction," by J. B. Johnson (5th Edition by Withey and Aston, 1917).
[5] "Concrete, Plain and Reinforced," by Taylor and Thompson (1905, 3rd Edition, 1916).

1. Workability or plasticity is an essential requirement of concrete and must be taken into account in designing the mixture. The workability of concrete for a given method of manipulation is controlled by:

a. Quantity of mixing water,
b. Quantity of cement,
c. Size and grading of aggregate,
d. Combinations of a, b and c.

Any combination of the constituent materials which produces concrete of a given water-ratio will result in concrete of approximately the same strength, so long as the concrete is workable.

2. For workable mixtures, the strength of concrete decreases as the water-ratio increases. The addition of 1 lb. of mixing water to a 1-sack batch reduces the strength of concrete as much as the omission of 1 to 2 lb. of cement.

3. The increase in strength with added cement is reflected by a decrease in the water-ratio. Richer mixtures of a given condition of workability can be produced with a lower water-ratio, and consequently give higher strengths.

4. The strength of concrete increases as coarser aggregates are used, so long as the mixture is workable. Finer aggregates require more water for a given workability and quantity of cement, and therefore give lower strengths than the coarse aggregates. There is an intimate relation between the size and grading of the aggregate and the quantity of water required to produce concrete of a given workability.

5. It is not necessary, or desirable, that the fine and coarse aggregates conform to fixed gradings; rather wide variations in gradings may occur without affecting the quantity of mixing water or the quality of the resulting concrete. Aggregates separated into any sizes may be so combined as to give desired results, so long as the grading will give workable concrete. The classification of material smaller than the No. 4 sieve as fine aggregate, and larger than this size as coarse aggregate, is purely arbitrary. Separation into at least two sizes is desirable as it greatly facilitates maintaining uniformity in successive batches; this method avoids the segregation which may occur in handling mixed aggregates.

The quantity of mixing water required for a given slump or flow will vary with the mix, and with size, type and grading of aggregate. The same quantity of mixing water per sack of cement is required for all of the proportions for a given strength. For example, the 2000-lb. per. sq. in. concrete requires a water-ratio of about 0.9, equivalent to 6.7 U. S. gallons (1 gal. = 231 cu. in.) of water per sack of cement, including the moisture held by the aggregates. (See Fig. 1.)

BASIS OF TABLES

The tables of this Bulletin are based on the water-ratio method of proportioning concrete. They consist of a tabulation of interpolated

values from the results of many thousands of tests covering a wide range of mixtures, consistencies and sizes and gradings of aggregate, systematically arranged in a manner convenient for use. In many cases the data have been extended to include values slightly outside the actual range covered by the tests, an extension which seems warranted by the agreement of the tests.

Proportions of fine and coarse aggregates have been selected which may be expected to give the highest strength consistent with proper workability for the quantity of cement used; in other words, the mixes generally contain the largest practicable amount of coarse aggregate. It may be expected that with some aggregates, the mixes in the tables will be somewhat too harsh for certain purposes.

The tests covered a wide range in grading of aggregates; the grading was fairly regular between limiting sizes. The tables, therefore, will give best results when similar gradings are used.

These tables are based on compression tests at 28 days of 6 by 12-in. concrete cylinders made and tested in accordance with "Tentative Method of Making Compression Tests of Concrete" of the American Society for Testing Materials. The proportions given cannot be expected to produce concrete of the strengths indicated unless the tests are carried out under similar conditions.

The workability of the various mixtures in the tests was compared by means of the "slump." Although not an absolute measure of workability, the slump is a convenient means of maintaining uniformity or of comparing the effect on workability of variations in proportions. The different consistencies in the tables are classified on this basis. The principal value of the slump test is in avoiding the habitual use of such an excess of mixing water as will *materially* lower the quality of the concrete. The specifications should indicate the workability of concrete desired for different types of construction. For the usual reinforced concrete work, the aim should be to use a slump of 6 to 7 in. or less; in mass work a slump of 1 to 4 in. may be used; for machine-finished concrete roads, a slump as low as 1 in. may be used.

The water-ratio-strength relation shown in Fig. 1 represents the lower range of 28-day strengths from 9 different series of tests. The proportions and quantities in the tables are designed to produce the designated slumps when the quantity of water required by Fig. 1 for the strengths given at the heads of the tables is used. The quantity of mixing water in gallons per sack of cement is indicated in each table.

The design and construction of reinforced concrete structures is generally based on the 28-day strength of concrete. For portland-cement concrete cured in a moist place at normal temperatures, the

compressive strengths at other ages compared to the strengths at 28 days are about as follows:

7 days	50 per cent
28 days	100 per cent
3 months	130 per cent
1 year	165 per cent

Tests made in this Laboratory and in others have shown that the 28-day compressive strength of concrete is a fairly accurate criterion of other desirable properties.

The factors which produce high compressive strength also produce high flexural strength and high resistance to wear. Impermeability and resistance to destructive agencies such as weather, sea and sulphate waters, etc., are increased by these same factors (increased cement content, improved gradings and lower water-ratio) where the workability of the concrete permits puddling readily into the forms.

The cement used in the tests forming the basis of the tables was a mixture of four brands meeting the requirements of "Standard Specifications and Tests for Portland Cement" of the A.S.T.M.

The tables apply only to aggregates which are clean, structurally sound and free from injurious amounts of shale, alkali, organic matter, silt and other deleterious substances.

The quantities of materials per cubic yard of concrete were determined from the "yield" of concrete puddled into 6 by 12-in. cylinders. The volume[6] of aggregates are based on dry and rodded measurements as used in the tests. The tables contain no allowance for waste nor bulking due to moisture and method of measuring on the work. It is impracticable and undesirable to base such tables on field proportions since wide differences occur in moisture content and in methods of handling on the job.

In the tests the concrete was mixed by hand in batches of about 1/5 cubic foot. The method of mixing was equivalent to about 1 minute of machine mixing. Most specifications require a minimum of 1 minute machine mixing.

PURPOSE OF TABLES

These tables are intended for use in all types of work to which plastic concrete[7] is applicable. It is not intended that they shall be a

[6]The *quantities* in the tables which are expressed in terms of volume, may be changed to weights by multiplying by the dry and rodded unit weights of the materials.

The *proportions* by volume may be changed to proportions by weight by multiplying by the dry and rodded weight per cubic foot of the aggregate and dividing by 94. If the weight of the sand were 115 and of the coarse aggregate 110 lb. per cu. ft., a 1-2.3-4.1 mix by volume would be 1-2.8-4.8 by weight.

[7]They are not directly applicable to concrete for the semi-dry mixtures used in machine-made products such as block, tile, etc.; the driest consistencies given in the tables would be too wet, and the aggregate sizes generally would be too large. However, the fundamental relations (between quantity of mixing water, quantity of cement, and size and grading of aggregate) apply to the "semi-dry" mixtures in essentially the same way as to plastic mixtures.

universal guide for the proportioning of concrete nor is it claimed that the proportions will be most satisfactory under all conditions. It is recommended that, wherever time and facilities permit and the importance of the work warrants, the selection of proportions be based on tests of concrete made from the aggregate to be used. For such tests, these tables will prove a useful guide in the selection of preliminary mixtures for trial or in eliminating extreme combinations.

The tables can be used as a basis of proportions for average conditions where tests cannot be made in advance of or during the work. They will also be useful in adjusting proportions to compensate for variations in the size or grading of aggregates or in the workability of concrete where it would be impracticable to await the results of tests.

The tables will be found useful for comparing material costs for preliminary estimates, where several materials are available and where the workability and strength requirements of the concrete are known. They illustrate the fact that aggregates of many different sizes and grading may be combined with equally good results in concrete and show that it is not necessary to restrict aggregate sizes or gradings to those usually mentioned in specifications.

CONVERSION OF PROPORTIONS AND QUANTITIES TO FIELD MEASUREMENTS

The quantities of aggregates in the tables are in terms of volumes measured *dry and rodded;* for use on the job quantities must be converted to terms of field measurements. For example, determine proportions for 3000-lb. per sq. in. concrete, slump 3 to 4 in., fine aggregate graded 0 to No. 4, coarse aggregate, No. 4 to 1½ in. The table (page 14) shows that the proportions are 1:1.4:2.9. Assume the bulking of the aggregates due to moisture and method of measurement (see Appendix 1), to be:

Fine aggregate—23%
Coarse " — 6%

To express the above proportions in terms of damp and loose volumes measured under field conditions, the volume of sand must be increased 23% and the coarse aggregate 6%; the field proportions will be:

$$1:(1.4\times1.23):(2.9\times1.06) \text{ or } 1:1.7:3.1$$

The volumes in the table of quantities must be increased by the same amounts; in terms of damp and loose measurements the quantities of aggregate will then be:

Fine — $.35\times1.23=.43$
Coarse — $.72\times1.06=.76$

(Text Continued on Page 20)

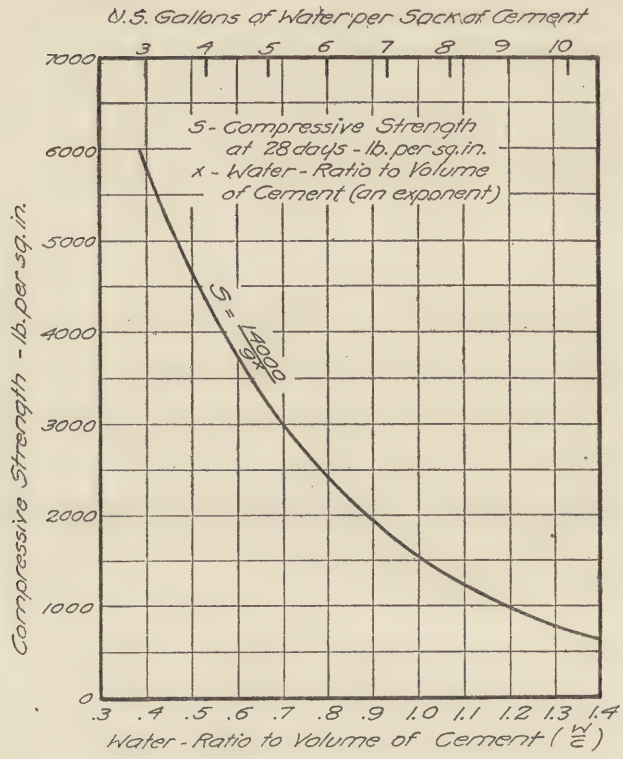


FIG. 1. EFFECT OF QUANTITY OF MIXING WATER ON THE COMPRESSIVE STRENGTH OF CONCRETE

S = compressive strength of concrete tested under standard conditions at 28 days; x (an exponent) = the water-ratio of the concrete, that is, ratio of volume of mixing water to volume of cement.

The above curve represents the most fundamental property of concrete, namely the dependence of concrete strength on quantity of mixing water. The curve may be represented by the equation $S = \frac{14000}{9^x}$. It gives strengths about 500 lb. per sq. in. lower than those given by the curve in Fig. 1, Bulletin 1. The curve in Bulletin 1 is represented by the equation $S = \frac{14000}{7^x}$ and gives the *average* range of concrete strengths while the former represents the *lower* range of concrete strengths based on 9 different series of tests.

LIMITATIONS OF TABLES AND PRECAUTIONS TO BE OBSERVED IN THEIR USE

1. The quantities of mixing water and cement are the most important factors in concrete and they should be accurately controlled.

2. The concrete must be plastic or workable. Too great reliance should not be placed on the slump test alone. If the concrete does not work into place or finish properly, the proportions of fine to coarse may be adjusted as required, so long as the quantity of water is maintained at the value given at the head of the table. Note that this quantity includes water contained in the aggregate. Absorption of aggregate can generally be neglected.

3. Where it is not practicable to exercise control over the consistency of the concrete, the proportions and quantities in BOLD FACE type, for a slump of 6 to 7 in., should be used.

4. Only portland cement meeting the requirements of the standard specifications should be used.

5. Aggregates should be clean, structurally sound, and graded between the sizes shown. The maximum and minimum sizes of the aggregate should be determined from sieve analyses. (See Appendix 1.)

6. Proportions and quantities in the tables are based on dry and rodded measurements. In proportioning on the job, proper allowance must be made for bulking of aggregates due to moisture content and loose measurement. (For methods of determining moisture and bulking, see Appendix 1.)

7. Strengths indicated in the tables are based on 28-day compression tests of 6 by 12-in. concrete cylinders puddled in the forms, cured in a damp place at normal temperatures and tested in a damp condition. In comparing the strengths of specimens made on the work, it is important that the tests be made in accordance with these standard methods.

8. Temperatures below normal will produce lower concrete strengths, especially at early ages, and allowances must be made accordingly.

9. Concrete should be mixed at least 1 minute in a batch mixer of standard make.

10. For concrete strengths, aggregate sizes, and slumps not covered by the tables, proportions and quantities may be determined by interpolation. (See page 20.)

Proportions for 2000 lb. per sq. in. Concrete

Based on 28-day compressive strength of 6 by 12-in. cylinders.

Mixing water, including moisture in aggregate, 6.7 gal. per sack of portland cement.

Proportions expressed in terms of dry and rodded volumes of aggregate.

Thus 1-1.7-3.4 indicates 1 volume of cement, 1.7 volumes of fine aggregate and 3.4 of coarse aggregate.

No allowance made for bulking of aggregates due to moisture or loose measurement.

For precautions to be observed in using tables see page 9.

Size of Coarse Aggregate	Slump, in.	Proportions Using Fine Aggregate of Different Sizes				
		0-No. 30	0-No. 16	0-No. 8	0-No. 4	0-⅜ in.
None	½ to 1	1:2.2	1:2.6	1:3.0	1:3.5	1:4.1
	3 " 4	1:1.9	1:2.2	1:2.6	1:3.0	1:3.5
	6 " 7	**1:1.5**	**1:1.7**	**1:2.0**	**1:2.3**	**1:2.7**
	8 " 10	1:1.0	1:1.1	1:1.3	1:1.6	1:1.8
No. 4 to ¾ in.	½ to 1	1:2.1:3.8	1:2.3:3.7	1:2.6:3.5	1:3.0:3.1	1:3.6:2.8
	3 " 4	1:1.7:3.3	1:1.9:3.2	1:2.2:3.1	1:2.6:2.8	1:3.0:2.4
	6 " 7	**1:1.3:2.7**	**1:1.4:2.6**	**1:1.7:2.5**	**1:1.9:2.3**	**1:2.3:2.1**
	8 " 10	1:0.8:1.9	1:0.9:1.9	1:1.0:1.8	1:1.2:1.7	1:1.5:1.6
No. 4 to 1 in.	½ to 1	1:1.9:4.5	1:2.2:4.3	1:2.5:4.2	1:2.8:3.9	1:3.4:3.6
	3 " 4	1:1.6:3.9	1:1.8:3.8	1:2.1:3.7	1:2.4:3.5	1:2.8:3.2
	6 " 7	**1:1.2:3.1**	**1:1.3:3.1**	**1:1.5:3.0**	**1:1.8:2.9**	**1:2.1:2.7**
	8 " 10	1:0.7:2.2	1:0.8:2.2	1:1.0:2.3	1:1.1:2.1	1:1.3:2.0
No. 4 to 1½ in	½ to 1	1:1.9:5.0	1:2.1:4.9	1:2.4:4.9	1:2.7:4.6	1:3.2:4.4
	3 " 4	1:1.6:4.4	1:1.7:4.3	1:2.0:4.2	1:2.4:4.0	1:2.7:3.8
	6 " 7	**1:1.1:3.5**	**1:1.3:3.5**	**1:1.4:3.5**	**1:1.7:3.4**	**1:2.0:3.2**
	8 " 10	1:0.7:2.5	1:0.8:2.5	1:0.9:2.5	1:1.0:2.4	1:1.2:2.3
No. 4 to 2 in.	½ to 1	1:1.7:5.8	1:1.9:5.7	1:2.1:5.8	1:2.4:5.6	1:2.8:5.5
	3 " 4	1:1.4:5.0	1:1.5:5.0	1:1.8:5.0	1:2.0:4.9	1:2.3:4.7
	6 " 7	**1:1.0:4.1**	**1:1.1:4.1**	**1:1.2:4.1**	**1:1.4:4.1**	**1:1.7:3.9**
	8 " 10	1:0.6:2.9	1:0.7:2.9	1:0.7:3.0	1:0.8:2.9	1:1.0:2.9
⅜ to 1 in.	½ to 1	1:2.2:4.4	1:2.5:4.2	1:2.8:4.1	1:3.3:3.8	1:3.8:3.4
	3 " 4	1:1.9:3.8	1:2.1:3.7	1:2.4:3.6	1:2.8:3.4	1:3.2:3.1
	6 " 7	**1:1.4:3.1**	**1:1.5:3.0**	**1:1.8:3.0**	**1:2.1:2.8**	**1:2.4:2.5**
	8 " 10	1:0.9:2.2	1:1.0:2.2	1:1.1:2.2	1:1.3:2.0	1:1.5:1.9
⅜ to 1½ in.	½ to 1	1:2.2:4.9	1:2.5:4.8	1:2.8:4.7	1:3.2:4.6	1:3.7:4.2
	3 " 4	1:1.9:4.3	1:2.1:4.2	1:2.4:4.1	1:2.7:4.0	1:3.1:3.7
	6 " 7	**1:1.4:3.5**	**1:1.5:3.4**	**1:1.7:3.4**	**1:2.0:3.3**	**1:2.3:3.1**
	8 " 10	1:0.9:2.5	1:1.0:2.5	1:1.1:2.4	1:1.3:2.4	1:1.5:2.1
⅜ to 2 in.	½ to 1	1:2.1:5.6	1:2.3:5.5	1:2.6:5.5	1:3.0:5.4	1:3.5:5.1
	3 " 4	1:1.7:4.8	1:2.0:4.8	1:2.2:4.8	1:2.5:4.7	1:2.9:4.4
	6 " 7	**1:1.3:4.0**	**1:1.4:3.9**	**1:1.6:3.9**	**1:1.8:3.9**	**1:2.1:3.8**
	8 " 10	1:0.8:2.9	1:0.9:2.9	1:1.0:2.9	1:1.2:2.9	1:1.3:2.8
¾ to 1½ in.	½ to 1	1:2.6:4.5	1:2.9:4.5	1:3.3:4.4	1:3.8:4.2	1:4.3:3.9
	3 " 4	1:2.2:3.9	1:2.5:3.9	1:2.8:3.8	1:3.2:3.6	1:3.6:3.3
	6 " 7	**1:1.6:3.2**	**1:1.8:3.2**	**1:2.1:3.1**	**1:2.4:3.0**	**1:2.7:2.8**
	8 " 10	1:1.0:2.3	1:1.2:2.3	1:1.4:2.2	1:1.6:2.2	1:1.8:2.1
¾ to 2 in.	½ to 1	1:2.5:5.2	1:2.8:5.2	1:3.2:5.1	1:3.6:5.0	1:4.1:4.7
	3 " 4	1:2.1:4.5	1:2.4:4.5	1:2.7:4.4	1:3.1:4.3	1:3.5:4.0
	6 " 7	**1:1.6:3.7**	**1:1.8:3.7**	**1:2.0:3.7**	**1:2.3:3.6**	**1:2.6:3.5**
	8 " 10	1:1.0:2.6	1:1.1:2.7	1:1.3:2.6	1:1.5:2.7	1:1.7:2.6
¾ to 3 in.	½ to 1	1:2.5:6.0	1:2.9:5.9	1:3.2:5.9	1:3.6:5.8	1:4.1:5.6
	3 " 4	1:2.1:5.1	1:2.4:5.2	1:2.7:5.2	1:3.1:5.1	1:3.5:4.9
	6 " 7	**1:1.5:4.1**	**1:1.7:4.2**	**1:2.0:4.2**	**1:2.3:4.2**	**1:2.5:4.0**
	8 " 10	1:1.0:2.9	1:1.1:3.0	1:1.3:3.0	1:1.5:3.0	1:1.7:3.6

Quantities of Materials for 1 cu. yd. of 2000 lb. per sq. in. Concrete

The volume of cement is expressed in barrels and of aggregates in cubic yards.

F = fine aggregate; C = coarse aggregate.

Quantities are net, no allowance being made for bulking or waste.

For precautions to be observed in using tables see page 9.

Size of Coarse Aggregate	Slump, in.	Quantities of Materials Using Fine Aggregate of Different Sizes														
		0-No. 30			0-No. 16			0-No. 8			0-No. 4			0-⅜ in.		
		Cement	Aggregate F.	Aggregate C.	Cement	Aggregate F.	Aggregate C.	Cement	Aggregate F.	Aggregate C.	Cement	Aggregate F.	Aggregate C.	Cement	Aggregate F.	Aggregate C.
None	½ to 1	2.31	.75		2.12	.82		1.92	.85		1.65	.85		1.42	.86	
	3 " 4	2.55	.72		2.39	.78		2.12	.82		1.85	.82		1.71	.89	
	6 " 7	**2.94**	**.65**		**2.83**	**.71**		**2.52**	**.75**		**2.24**	**.76**		**2.06**	**.83**	
	8 " 10	3.60	.53		3.54	.58		3.25	.62		2.80	.66		2.62	.70	
No. 4 to ¾ in.	½ to 1	1.27	.40	.71	1.24	.42	.68	1.19	.46	.62	1.17	.52	.54	1.17	.62	.48
	3 " 4	1.43	.36	.70	1.40	.39	.66	1.36	.44	.62	1.34	.51	.56	1.32	.59	.47
	6 " 7	**1.71**	**.33**	**.68**	**1.70**	**.35**	**.66**	**1.66**	**.42**	**.61**	**1.60**	**.45**	**.54**	**1.59**	**.54**	**.50**
	8 " 10	2.25	.27	.63	2.23	.30	.63	2.20	.33	.59	2.13	.38	.54	2.10	.47	.50
No. 4 to 1 in.	½ to 1	1.19	.33	.79	1.17	.38	.74	1.13	.42	.70	1.10	.46	.64	1.09	.55	.58
	3 " 4	1.36	.32	.78	1.32	.35	.74	1.26	.39	.69	1.24	.44	.64	1.24	.51	.59
	6 " 7	**1.65**	**.29**	**.76**	**1.62**	**.31**	**.74**	**1.56**	**.35**	**.69**	**1.52**	**.40**	**.65**	**1.51**	**.47**	**.60**
	8 " 10	2.15	.22	.70	2.13	.25	.69	2.07	.31	.70	2.01	.33	.63	1.98	.38	.59
No. 4 to 1½ in.	½ to 1	1.10	.31	.81	1.09	.34	.79	1.07	.38	.78	1.05	.42	.71	1.04	.49	.68
	3 " 4	1.26	.30	.82	1.25	.31	.79	1.20	.35	.74	1.17	.42	.69	1.16	.46	.65
	6 " 7	**1.54**	**.25**	**.80**	**1.52**	**.29**	**.79**	**1.47**	**.30**	**.76**	**1.44**	**.36**	**.72**	**1.43**	**.42**	**.68**
	8 " 10	2.04	.21	.75	2.00	.24	.74	1.94	.26	.72	1.88	.28	.67	1.88	.33	.64
No. 4 to 2 in.	½ to 1	1.04	.26	.89	1.05	.29	.88	1.04	.32	.89	1.00	.35	.83	.98	.41	.80
	3 " 4	1.20	.25	.89	1.19	.26	.88	1.16	.31	.86	1.11	.33	.80	1.12	.38	.78
	6 " 7	**1.47**	**.22**	**.89**	**1.45**	**.24**	**.88**	**1.38**	**.25**	**.84**	**1.35**	**.28**	**.82**	**1.36**	**.34**	**.79**
	8 " 10	1.92	.17	.82	1.89	.20	.81	1.85	.19	.82	1.81	.21	.78	1.80	.27	.77
⅜ to 1 in.	½ to 1	1.17	.38	.76	1.16	.43	.72	1.12	.46	.68	1.10	.54	.62	1.10	.62	.55
	3 " 4	1.34	.38	.75	1.33	.41	.73	1.29	.46	.69	1.23	.51	.62	1.23	.58	.56
	6 " 7	**1.67**	**.35**	**.77**	**1.63**	**.36**	**.72**	**1.57**	**.42**	**.70**	**1.51**	**.47**	**.63**	**1.53**	**.54**	**.57**
	8 " 10	2.16	.29	.70	2.12	.31	.69	2.06	.34	.67	2.01	.39	.60	1.93	.43	.54
⅜ to 1½ in.	½ to 1	1.10	.36	.80	1.07	.40	.76	1.05	.43	.73	1.02	.48	.69	1.03	.56	.64
	3 " 4	1.25	.35	.79	1.24	.39	.77	1.21	.43	.73	1.16	.46	.69	1.15	.53	.63
	6 " 7	**1.54**	**.32**	**.80**	**1.52**	**.34**	**.77**	**1.47**	**.37**	**.74**	**1.42**	**.42**	**.69**	**1.41**	**.48**	**.65**
	8 " 10	2.05	.27	.76	2.00	.29	.74	1.93	.31	.70	1.89	.36	.67	1.83	.41	.62
⅜ to 2 in.	½ to 1	1.05	.33	.85	1.03	.35	.84	1.01	.39	.82	.98	.43	.78	.97	.50	.73
	3 " 4	1.19	.30	.85	1.18	.35	.84	1.14	.37	.81	1.10	.41	.76	1.09	.47	.71
	6 " 7	**1.46**	**.28**	**.86**	**1.45**	**.30**	**.84**	**1.40**	**.33**	**.81**	**1.33**	**.35**	**.77**	**1.31**	**.41**	**.74**
	8 " 10	1.91	.23	.82	1.88	.25	.81	1.83	.27	.79	1.80	.32	.77	1.74	.34	.72
¾ to 1½ in.	½ to 1	1.07	.41	.71	1.06	.45	.71	1.02	.50	.66	.98	.55	.61	.98	.62	.57
	3 " 4	1.23	.40	.71	1.23	.45	.71	1.19	.49	.67	1.12	.53	.60	1.10	.59	.54
	6 " 7	**1.51**	**.36**	**.72**	**1.49**	**.40**	**.71**	**1.45**	**.45**	**.67**	**1.36**	**.48**	**.60**	**1.36**	**.54**	**.56**
	8 " 10	2.01	.30	.69	1.97	.35	.67	1.91	.40	.62	1.81	.43	.59	1.79	.48	.56
¾ to 2 in.	½ to 1	1.02	.38	.79	1.02	.42	.78	.99	.47	.75	.94	.50	.70	.93	.56	.65
	3 " 4	1.17	.36	.78	1.16	.41	.77	1.11	.44	.72	1.05	.48	.67	1.04	.54	.61
	6 " 7	**1.44**	**.34**	**.79**	**1.41**	**.38**	**.77**	**1.37**	**.41**	**.75**	**1.31**	**.45**	**.70**	**1.26**	**.48**	**.65**
	8 " 10	1.88	.28	.72	1.85	.30	.74	1.82	.35	.70	1.74	.39	.69	1.70	.43	.65
¾ to 3 in.	½ to 1	.96	.36	.85	.95	.41	.83	.92	.44	.80	.88	.47	.75	.86	.52	.71
	3 " 4	1.08	.34	.81	1.08	.38	.83	1.05	.42	.81	1.00	.46	.76	.98	.51	.71
	6 " 7	**1.36**	**.30**	**.83**	**1.30**	**.33**	**.81**	**1.28**	**.38**	**.80**	**1.23**	**.42**	**.77**	**1.20**	**.44**	**.71**
	8 " 10	1.81	.27	.78	1.76	.29	.78	1.72	.33	.76	1.65	.37	.73	1.60	.40	.71

Proportions for 2500 lb. per sq. in. Concrete

Based on 28-day compressive strength of 6 by 12-in. cylinders.

Mixing water, including moisture in aggregate, 5.9 gal. per sack of portland cement.

Proportions expressed in terms of dry and rodded volumes of aggregate.

Thus, 1-1.3-2.8 indicates 1 volume of cement, 1.3 volumes of fine aggregate and 2.8 of coarse aggregate.

No allowance made for bulking of aggregates due to moisture or loose measurement.

For precautions to be observed in using tables see page 9.

Size of Coarse Aggregate	Slump, in.	Proportions Using Fine Aggregate of Different Sizes				
		0-No. 30	0-No. 16	0-No. 8	0-No. 4	0-⅜ in.
None	½ to 1	1:1.8	1:2.1	1:2.4	1:2.9	1:3.3
	3 " 4	1:1.5	1:1.8	1:2.1	1:2.4	1:2.8
	6 " 7	**1:1.1**	**1:1.3**	**1:1.6**	**1:1.8**	**1:2.1**
	8 " 10	1:0.7	1:0.8	1:0.9	1:1.1	1:1.3
No. 4 to ¾ in.	½ to 1	1:1.6:3.2	1:1.8:3.1	1:2.1:3.0	1:2.4:2.7	1:2.9:2.4
	3 " 4	1:1.3:2.8	1:1.5:2.7	1:1.7:2.6	1:2.0:2.4	1:2.4:2.2
	6 " 7	**1:1.0:2.2**	**1:1.1:2.2**	**1:1.3:2.1**	**1:1.5:2.0**	**1:1.8:1.8**
	8 " 10	1:0.5:1.4	1:0.6:1.4	1:0.7:1.4	1:0.8:1.4	1:1.0:1.3
No. 4 to 1 in.	½ to 1	1:1.5:3.7	1:1.7:3.7	1:2.0:3.5	1:2.2:3.4	1:2.7:3.1
	3 " 4	1:1.2:3.3	1:1.4:3.2	1:1.6:3.1	1:1.9:3.0	1:2.2:2.7
	6 " 7	**1:0.9:2.6**	**1:1.0:2.5**	**1:1.1:2.5**	**1:1.3:2.4**	**1:1.6:2.3**
	8 " 10	1:0.5:1.7	1:0.6:1.7	1:0.6:1.7	1:0.7:1.6	1:0.9:1.5
No. 4 to 1½ in.	½ to 1	1:1.4:4.2	1:1.6:4.1	1:1.9:4.1	1:2.2:4.0	1:2.5:3.8
	3 " 4	1:1.2:3.7	1:1.3:3.6	1:1.5:3.6	1:1.8:3.5	1:2.1:3.3
	6 " 7	**1:0.9:2.9**	**1:0.9:2.8**	**1:1.1:2.8**	**1:1.3:2.8**	**1:1.5:2.6**
	8 " 10	1:0.5:1.9	1:0.5:1.9	1:0.6:1.9	1:0.7:1.8	1:0.8:1.8
No. 4 to 2 in.	½ to 1	1:1.3:4.9	1:1.4:4.8	1:1.6:4.9	1:1.9:4.8	1:2.2:4.7
	3 " 4	1:1.1:4.3	1:1.2:4.2	1:1.3:4.3	1:1.6:4.2	1:1.8:4.1
	6 " 7	**1:0.7:3.3**	**1:0.8:3.3**	**1:0.9:3.4**	**1:1.1:3.3**	**1:1.2:3.3**
	8 " 10	1:0.4:2.2	1:0.4:2.2	1:0.5:2.2	1:0.6:2.2	1:0.6:2.2
⅜ to 1 in.	½ to 1	1:1.8:3.7	1:2.0:3.6	1:2.3:3.5	1:2.6:3.3	1:3.0:2.9
	3 " 4	1:1.4:3.2	1:1.6:3.1	1:1.9:2.9	1:2.2:2.9	1:2.5:2.6
	6 " 7	**1:1.0:2.5**	**1:1.2:2.5**	**1:1.3:2.4**	**1:1.6:2.3**	**1:1.8:2.2**
	8 " 10	1:0.6:1.6	1:0.7:1.6	1:0.8:1.6	1:0.9:1.6	1:1.0:1.5
⅜ to 1½ in.	½ to 1	1:1.7:4.1	1:1.9:4.1	1:2.2:4.0	1:2.5:3.9	1:2.9:3.6
	3 " 4	1:1.5:3.6	1:1.6:3.6	1:1.8:3.5	1:2.1:3.4	1:2.3:3.2
	6 " 7	**1:1.0:2.9**	**1:1.2:2.8**	**1:1.3:2.8**	**1:1.5:2.7**	**1:1.8:2.6**
	8 " 10	1:0.6:1.9	1:0.6:1.9	1:0.8:1.8	1:0.9:1.8	1:1.0:1.8
⅜ to 2 in.	½ to 1	1:1.7:4.7	1:1.8:4.7	1:2.1:4.7	1:2.4:4.6	1:2.7:4.4
	3 " 4	1:1.4:4.1	1:1.5:4.1	1:1.7:4.1	1:2.0:4.0	1:2.3:3.9
	6 " 7	**1:1.0:3.2**	**1:1.1:3.2**	**1:1.2:3.2**	**1:1.4:3.2**	**1:1.6:3.1**
	8 " 10	1:0.5:2.1	1:0.6:2.1	1:0.7:2.2	1:0.8:2.2	1:0.9:2.1
¾ to 1½ in.	½ to 1	1:2.0:3.8	1:2.3:3.8	1:2.6:3.7	1:3.0:3.6	1:3.4:3.3
	3 " 4	1:1.7:3.3	1:2.0:3.3	1:2.2:3.2	1:2.5:3.2	1:2.9:2.9
	6 " 7	**1:1.2:2.6**	**1:1.4:2.6**	**1:1.6:2.6**	**1:1.9:2.5**	**1:2.1:2.3**
	8 " 10	1:0.7:1.7	1:0.8:1.7	1:0.9:1.7	1:1.1:1.7	1:1.2:1.6
¾ to 2 in.	½ to 1	1:2.0:4.4	1:2.2:4.4	1:2.5:4.3	1:2.9:4.3	1:3.3:4.1
	3 " 4	1:1.7:3.8	1:1.9:3.8	1:2.1:3.8	1:2.5:3.7	1:2.8:3.6
	6 " 7	**1:1.2:3.0**	**1:1.4:3.0**	**1:1.5:3.0**	**1:1.8:3.0**	**1:2.0:2.8**
	8 " 10	1:0.7:2.0	1:0.8:2.0	1:0.9:2.0	1:1.0:2.0	1:1.2:2.0
¾ to 3 in.	½ to 1	1:2.0:5.0	1:2.2:5.0	1:2.5:5.0	1:2.7:5.0	1:3.2:4.7
	3 " 4	1:1.7:4.3	1:1.9:4.3	1:2.1:4.3	1:2.4:4.3	1:2.7:4.1
	6 " 7	**1:1.2:3.3**	**1:1.4:3.4**	**1:1.5:3.4**	**1:1.8:3.4**	**1:2.0:3.3**
	8 " 10	1:0.7:2.2	1:0.8:2.2	1:0.9:2.2	1:1.0:2.3	1:1.2:2.3

Quantities of Materials for 1 cu. yd. of 2500 lb. per sq. in. Concrete

The volume of cement is expressed in barrels and of aggregates in cubic yards.

F = fine aggregate; C = coarse aggregate.

Quantities are net, no allowance being made for bulking or waste.

For precautions to be observed in using tables see page 9.

Size of Coarse Aggregate	Slump, in.	Quantities of Materials Using Fine Aggregate of Different Sizes											
		0-No. 30			0-No. 16			0-No. 8			0-No. 4			0-⅜ in.		
		Cement	Aggregate F.	Aggregate C.	Cement	Aggregate F.	Aggregate C.	Cement	Aggregate F.	Aggregate C.	Cement	Aggregate F.	Aggregate C.	Cement	Aggregate F.	Aggregate C.
None	½ to 1	2.71	.72		2.53	.79		2.30	.82		1.94	.83		1.83	.89	
	3 " 4	3.01	.67		2.78	.74		2.50	.78		2.20	.78		2.05	.85	
	6 " 7	**3.60**	**.59**		**3.38**	**.65**		**2.97**	**.70**		**2.71**	**.72**		**2.45**	**.76**	
	8 " 10	4.24	.44		4.11	.49		3.91	.52		3.46	.56		3.16	.61	
No. 4 to ¾ in.	½ to 1	1.49	.35	.70	1.46	.39	.67	1.42	.44	.63	1.39	.49	.55	1.39	.60	.49
	3 " 4	1.68	.32	.70	1.67	.37	.67	1.63	.41	.63	1.57	.46	.56	1.54	.55	.50
	6 " 7	**2.06**	**.30**	**.67**	**2.03**	**.33**	**.66**	**1.98**	**.38**	**.62**	**1.89**	**.42**	**.56**	**1.89**	**.50**	**.50**
	8 " 10	2.83	.21	.59	2.78	.25	.58	2.71	.28	.56	2.64	.31	.55	2.58	.38	.50
No. 4 to 1 in.	½ to 1	1.42	.32	.78	1.39	.35	.76	1.35	.40	.70	1.30	.42	.65	1.29	.51	.59
	3 " 4	1.61	.29	.79	1.56	.32	.74	1.51	.36	.69	1.48	.41	.65	1.47	.48	.59
	6 " 7	**1.95**	**.26**	**.75**	**1.90**	**.28**	**.70**	**1.87**	**.30**	**.69**	**1.82**	**.35**	**.65**	**1.81**	**.43**	**.62**
	8 " 10	2.68	.19	.65	2.64	.23	.66	2.54	.23	.64	2.50	.26	.59	2.58	.33	.55
No. 4 to 1½ in.	½ to 1	1.34	.27	.83	1.32	.31	.80	1.25	.35	.76	1.23	.40	.73	1.23	.45	.69
	3 " 4	1.50	.27	.82	1.48	.28	.79	1.43	.32	.76	1.39	.37	.72	1.39	.43	.68
	6 " 7	**1.83**	**.24**	**.79**	**1.83**	**.24**	**.76**	**1.78**	**.29**	**.74**	**1.73**	**.33**	**.72**	**1.72**	**.38**	**.66**
	8 " 10	2.50	.19	.70	2.49	.18	.70	2.42	.21	.68	2.40	.25	.64	2.39	.28	.64
No. 4 to 2 in.	½ to 1	1.25	.24	.91	1.24	.26	.88	1.21	.29	.88	1.17	.33	.83	1.13	.37	.79
	3 " 4	1.44	.23	.92	1.41	.25	.88	1.36	.26	.87	1.31	.31	.81	1.32	.35	.80
	6 " 7	**1.77**	**.18**	**.87**	**1.75**	**.21**	**.86**	**1.70**	**.23**	**.86**	**1.65**	**.27**	**.81**	**1.63**	**.29**	**.80**
	8 " 10	2.43	.14	.79	2.42	.14	.79	2.38	.18	.78	2.32	.21	.75	2.31	.20	.75
⅜ to 1 in.	½ to 1	1.41	.38	.77	1.39	.41	.74	1.34	.46	.69	1.29	.50	.63	1.29	.57	.55
	3 " 4	1.61	.33	.76	1.57	.37	.72	1.51	.42	.65	1.47	.48	.63	1.45	.54	.56
	6 " 7	**1.97**	**.29**	**.73**	**1.91**	**.34**	**.71**	**1.87**	**.36**	**.66**	**1.83**	**.43**	**.62**	**1.78**	**.47**	**.58**
	8 " 10	2.64	.23	.62	2.62	.27	.62	2.56	.30	.61	2.47	.33	.58	2.42	.36	.54
⅜ to 1½ in.	½ to 1	1.32	.33	.80	1.30	.37	.79	1.27	.41	.75	1.22	.45	.70	1.21	.52	.64
	3 " 4	1.49	.33	.79	1.48	.35	.79	1.43	.38	.74	1.38	.43	.69	1.37	.47	.65
	6 " 7	**1.86**	**.28**	**.80**	**1.83**	**.33**	**.76**	**1.77**	**.34**	**.74**	**1.73**	**.38**	**.69**	**1.68**	**.45**	**.65**
	8 " 10	2.49	.22	.70	2.46	.22	.69	2.41	.29	.64	2.38	.32	.63	2.32	.34	.62
⅜ to 2 in.	½ to 1	1.24	.31	.86	1.23	.33	.85	1.09	.34	.76	1.15	.41	.78	1.12	.45	.73
	3 " 4	1.41	.29	.85	1.40	.31	.85	1.35	.34	.82	1.29	.38	.76	1.28	.44	.74
	6 " 7	**1.77**	**.26**	**.84**	**1.74**	**.28**	**.82**	**1.68**	**.30**	**.80**	**1.62**	**.34**	**.77**	**1.58**	**.38**	**.73**
	8 " 10	2.41	.18	.75	2.37	.21	.74	2.32	.24	.76	2.30	.27	.75	2.22	.30	.69
¾ to 1½ in.	½ to 1	1.30	.38	.73	1.29	.44	.72	1.21	.47	.66	1.18	.52	.63	1.16	.58	.57
	3 " 4	1.47	.37	.72	1.45	.43	.71	1.40	.46	.66	1.35	.50	.64	1.32	.57	.57
	6 " 7	**1.80**	**.32**	**.69**	**1.80**	**.37**	**.69**	**1.75**	**.42**	**.67**	**1.67**	**.47**	**.62**	**1.64**	**.51**	**.60**
	8 " 10	2.48	.26	.63	2.45	.29	.62	2.40	.32	.60	2.31	.38	.58	2.27	.40	.54
¾ to 2 in.	½ to 1	1.22	.36	.79	1.22	.40	.79	1.18	.44	.75	1.10	.47	.70	1.07	.52	.65
	3 " 4	1.41	.35	.79	1.38	.39	.77	1.33	.41	.75	1.27	.47	.69	1.23	.51	.65
	6 " 7	**1.74**	**.31**	**.77**	**1.70**	**.35**	**.76**	**1.66**	**.37**	**.74**	**1.58**	**.42**	**.70**	**1.53**	**.45**	**.64**
	8 " 10	2.40	.25	.71	2.36	.28	.70	2.29	.31	.68	2.22	.33	.60	2.17	.38	.64
¾ to 3 in.	½ to 1	1.15	.34	.85	1.13	.37	.84	1.10	.41	.81	1.05	.42	.78	1.02	.48	.71
	3 " 4	1.33	.33	.84	1.30	.37	.83	1.25	.39	.79	1.21	.43	.77	1.18	.47	.72
	6 " 7	**1.67**	**.30**	**.82**	**1.59**	**.33**	**.80**	**1.55**	**.34**	**.78**	**1.49**	**.40**	**.75**	**1.45**	**.43**	**.71**
	8 " 10	2.32	.24	.75	2.27	.27	.74	2.20	.29	.72	2.13	.32	.73	2.12	.38	.72

Proportions for 3000 lb. per sq. in. Concrete

Based on 28-day compressive strength of 6 by 12-in. cylinders.

Mixing water, including moisture in aggregate, 5.2 gal. per sack of portland cement.

Proportions expressed in terms of dry and rodded volumes of aggregate.

Thus, 1-0.9-2.2 indicates 1 volume of cement, 0.9 volumes of fine aggregate and 2.2 of coarse aggregate.

No allowance made for bulking of aggregates due to moisture or loose measurement.

For precautions to be observed in using tables see page 9.

Size of Coarse Aggregate	Slump, in.	Proportions Using Fine Aggregate of Different Sizes				
		0-No. 30	0-No. 16	0-No. 8	0-No. 4	0-⅜ in.
None	½ to 1	1:1.5	1:1.7	1:2.0	1:2.3	1:2.7
	3 " 4	1:1.2	1:1.4	1:1.7	1:1.9	1:2.3
	6 " 7	**1:0.9**	**1:1.0**	**1:1.2**	**1:1.4**	**1:1.6**
	8 " 10	1:0.5	1:0.6	1:0.7	1:0.8	1:0.9
No. 4 to ¾ in.	½ to 1	1:1.3:2.7	1:1.5:2.6	1:1.7:2.5	1:1.9:2.4	1:2.3:2.1
	3 " 4	1:1.0:2.3	1:1.2:2.2	1:1.4:2.2	1:1.6:2.0	1:1.9:1.8
	6 " 7	**1:0.7:1.7**	**1:0.8:1.7**	**1:0.9:1.7**	**1:1.1:1.6**	**1:1.3:1.4**
	8 " 10	1:0.3:1.0	1:0.4:1.0	1:0.5:1.0	1:0.5:1.0	1:0.6:0.9
No. 4 to 1 in.	½ to 1	1:1.2:3.1	1:1.3:3.1	1:1.5:3.0	1:1.8:2.9	1:2.1:2.7
	3 " 4	1:0.9:2.7	1:1.1:2.6	1:1.2:2.6	1:1.4:2.5	1:1.7:2.3
	6 " 7	**1:0.6:2.0**	**1:0.7:2.0**	**1:0.8:2.0**	**1:0.9:1.9**	**1:1.1:1.8**
	8 " 10	1:0.3:1.2	1:0.3:1.2	1:0.4:1.2	1:0.5:1.2	1:0.6:1.2
No. 4 to 1½ in.	½ to 1	1:1.1:3.6	1:1.2:3.5	1:1.5:3.5	1:1.7:3.4	1:2.0:3.2
	3 " 4	1:0.9:3.0	1:1.0:2.9	1:1.2:2.9	1:1.4:2.9	1:1.6:2.7
	6 " 7	**1:0.6:2.2**	**1:0.7:2.2**	**1:0.8:2.2**	**1:0.9:2.2**	**1:1.1:2.1**
	8 " 10	1:0.3:1.4	1:0.3:1.3	1:0.4:1.4	1:0.5:1.4	1:0.5:1.3
No. 4 to 2 in.	½ to 1	1:1.0:4.1	1:1.1:4.1	1:1.2:4.1	1:1.4:4.1	1:1.6:4.0
	3 " 4	1:0.8:3.4	1:0.9:3.4	1:1.0:3.5	1:1.1:3.4	1:1.3:3.4
	6 " 7	**1:0.5:2.6**	**1:0.6:2.6**	**1:0.6:2.7**	**1:0.7:2.6**	**1:0.9:2.6**
	8 " 10	1:0.2:1.6	1:0.3:1.6	1:0.3:1.7	1:0.4:1.7	1:0.4:1.7
⅜ to 1 in.	½ to 1	1:1.4:3.1	1:1.5:3.0	1:1.8:2.9	1:2.1:2.8	1:2.4:2.6
	3 " 4	1:1.1:2.6	1:1.3:2.6	1:1.5:2.5	1:1.7:2.4	1:2.0:2.2
	6 " 7	**1:0.8:2.0**	**1:0.8:2.0**	**1:1.0:1.9**	**1:1.1:1.9**	**1:1.3:1.8**
	8 " 10	1:0.4:1.2	1:0.4:1.2	1:0.5:1.2	1:0.6:1.2	1:0.7:1.1
⅜ to 1½ in.	½ to 1	1:1.4:3.5	1:1.5:3.4	1:1.7:3.4	1:2.0:3.3	1:2.3:3.1
	3 " 4	1:1.1:3.0	1:1.2:2.9	1:1.4:2.9	1:1.6:2.8	1:1.9:2.6
	6 " 7	**1:0.8:2.2**	**1:0.8:2.2**	**1:1.0:2.2**	**1:1.1:2.1**	**1:1.3:2.0**
	8 " 10	1:0.4:1.4	1:0.4:1.4	1:0.5:1.4	1:0.6:1.3	1:0.7:1.3
⅜ to 2 in.	½ to 1	1:1.3:4.0	1:1.4:4.0	1:1.6:4.0	1:1.9:3.9	1:2.1:3.8
	3 " 4	1:1.0:3.4	1:1.2:3.4	1:1.3:3.3	1:1.5:3.3	1:1.7:3.2
	6 " 7	**1:0.7:2.6**	**1:0.8:2.5**	**1:0.9:2.6**	**1:1.0:2.6**	**1:1.1:2.5**
	8 " 10	1:0.4:1.6	1:0.4:1.6	1:0.5:1.6	1:0.5:1.6	1:0.6:1.6
¾ to 1½ in.	½ to 1	1:1.6:3.2	1:1.8:3.2	1:2.1:3.2	1:2.4:3.1	1:2.7:2.9
	3 " 4	1:1.3:2.7	1:1.5:2.7	1:1.7:2.7	1:2.0:2.6	1:2.3:2.5
	6 " 7	**1:0.9:2.0**	**1:1.0:2.1**	**1:1.2:2.0**	**1:1.4:2.0**	**1:1.5:1.8**
	8 " 10	1:0.5:1.2	1:0.5:1.3	1:0.6:1.3	1:0.7:1.3	1:0.8:1.2
¾ to 2 in.	½ to 1	1:1.6:3.7	1:1.8:3.7	1:2.0:3.7	1:2.4:3.6	1:2.6:3.5
	3 " 4	1:1.3:3.1	1:1.5:3.1	1:1.6:3.1	1:1.9:3.1	1:2.2:3.0
	6 " 7	**1:0.9:2.4**	**1:1.1:2.4**	**1:1.3:2.4**	**1:1.3:2.4**	**1:1.5:2.3**
	8 " 10	1:0.5:1.5	1:0.5:1.5	1:0.6:1.5	1:0.7:1.5	1:0.8:1.5
¾ to 3 in.	½ to 1	1:1.6:4.2	1:1.8:4.2	1:2.0:4.2	1:2.3:4.1	1:2.6:4.0
	3 " 4	1:1.3:3.5	1:1.5:3.6	1:1.6:3.6	1:1.9:3.6	1:2.1:3.5
	6 " 7	**1:0.9:2.6**	**1:1.0:2.6**	**1:1.1:2.6**	**1:1.3:2.6**	**1:1.4:2.6**
	8 " 10	1:0.5:1.6	1:0.5:1.6	1:0.6:1.7	1:0.7:1.7	1:0.8:1.7

Quantities of Materials for 1 cu. yd. of 3000 lb. per sq. in. Concrete

The volume of cement is expressed in barrels and of aggregates in cubic yards.

F = fine aggregate; C = coarse aggregate.

Quantities are net, no allowance being made for bulking or waste.

For precautions to be observed in using tables see page 9.

Size of Coarse Aggregate	Slump, in.	Quantities of Materials Using Fine Aggregate of Different Sizes											
		0-No. 30			0-No. 16			0-No. 8			0-No. 4			0-⅜ in.		
		Cement	Aggregate F.	Aggregate C.	Cement	Aggregate F.	Aggregate C.	Cement	Aggregate F.	Aggregate C.	Cement	Aggregate F.	Aggregate C.	Cement	Aggregate F.	Aggregate C.
None	½ to 1	3.08	.68		2.96	.74		2.65	.78		2.34	.80		2.14	.86	
	3 " 4	3.61	.64		3.31	.69		2.93	.74		2.66	.75		2.37	.81	
	6 " 7	**3.99**	**.53**		**3.79**	**.56**		**3.57**	**.63**		**3.18**	**.66**		**2.93**	**.69**	
	8 " 10	4.77	.35		4.63	.41		4.34	.45		3.93	.47		3.79	.50	
No. 4 to ¾ in.	½ to 1	1.75	.34	.70	1.73	.38	.66	1.69	.42	.63	1.63	.46	.58	1.59	.54	.49
	3 " 4	2.00	.30	.68	1.97	.35	.64	1.93	.40	.63	1.86	.44	.55	1.86	.52	.49
	6 " 7	**2.48**	**.26**	**.62**	**2.46**	**.29**	**.62**	**2.38**	**.32**	**.60**	**2.37**	**.39**	**.56**	**2.35**	**.45**	**.49**
	8 " 10	3.46	.15	.51	3.44	.20	.51	3.38	.25	.50	3.34	.25	.49	3.31	.29	.44
No. 4 to 1 in.	½ to 1	1.68	.30	.77	1.65	.32	.76	1.60	.36	.71	1.55	.41	.66	1.53	.47	.61
	3 " 4	1.88	.25	.75	1.86	.30	.72	1.83	.32	.70	1.78	.37	.66	1.76	.44	.60
	6 " 7	**2.39**	**.21**	**.71**	**2.38**	**.25**	**.70**	**2.32**	**.27**	**.69**	**2.27**	**30**	**.64**	**2.26**	**.37**	**.60**
	8 " 10	3.32	.15	.59	3.30	.15	.59	3.25	.19	.58	3.21	24	.57	3.18	.28	.56
No. 4 to 1½ in.	½ to 1	1.58	.23	.84	1.55	.28	.80	1.50	.33	.78	1.46	.37	.73	1.46	.43	.69
	3 " 4	1.80	.24	.80	1.78	.26	.76	1.73	.31	.74	1.68	.35	.72	1.67	.40	.67
	6 " 7	**2.30**	**.20**	**.75**	**2.27**	**.24**	**.74**	**2.21**	**.26**	**.72**	**2.15**	**.29**	**.70**	**2.12**	**.35**	**.66**
	8 " 10	3.19	.14	.66	3.17	.14	.61	3.09	.18	.64	3.04	.22	.63	3.02	.22	.58
No. 4 to 2 in.	½ to 1	1.50	.22	.91	1.49	.24	.90	1.43	.25	.87	1.38	.29	.84	1.38	.33	.82
	3 " 4	1.73	.20	.87	1.71	.23	.86	1.65	.24	.85	1.60	.26	.81	1.60	.31	.80
	6 " 7	**2.18**	**.16**	**.84**	**2.14**	**.19**	**.82**	**2.06**	**.18**	**.82**	**2.01**	**.21**	**.77**	**2.01**	**.27**	**.77**
	8 " 10	3.12	.09	.74	3.09	.14	.73	3.04	.14	.76	2.94	.17	.74	2.94	.17	.74
⅜ to 1 in.	½ to 1	1.69	.35	.77	1.65	.37	.73	1.60	.43	.69	1.54	.48	.64	1.51	.54	.58
	3 " 4	1.91	.31	.73	1.88	.36	.72	1.82	.40	.67	1.78	.45	.63	1.73	.51	.56
	6 " 7	**2.40**	**.28**	**.71**	**2.36**	**.28**	**.70**	**2.31**	**.34**	**.65**	**2.26**	**.37**	**.64**	**2.19**	**.42**	**.58**
	8 " 10	3.23	.19	.57	3.21	.19	.57	3.15	.23	.56	3.00	.27	.53	2.93	.30	.48
⅜ to 1½ in.	½ to 1	1.57	.32	.81	1.55	.34	.78	1.50	.38	.75	1.45	.43	.71	1.43	.49	.66
	3 " 4	1.81	.30	.81	1.78	.32	.76	1.73	.36	.74	1.68	.40	.70	1.63	.46	.63
	6 " 7	**2.30**	**.20**	**.75**	**2.26**	**.27**	**.74**	**2.20**	**.33**	**.72**	**2.15**	**.35**	**.67**	**2.08**	**.35**	**.62**
	8 " 10	2.97	.18	.61	2.94	.17	.61	2.88	.21	.60	2.87	.26	.60	2.78	.30	.55
⅜ to 2 in.	½ to 1	1.49	.29	.88	1.48	.32	.88	1.42	.34	.84	1.36	.38	.77	1.34	.42	.75
	3 " 4	1.73	.26	.87	1.70	.30	.86	1.63	.31	.80	1.58	.35	.77	1.55	.39	.73
	6 " 7	**2.18**	**.23**	**.84**	**2.12**	**.25**	**.79**	**2.05**	**.27**	**.79**	**2.01**	**.30**	**.77**	**1.93**	**.31**	**.72**
	8 " 10	2.98	.18	.71	2.99	.18	.71	2.90	.21	.69	2.93	.22	.69	2.84	.25	.67
¾ to 1½ in.	½ to 1	1.55	.37	.73	1.52	.40	.72	1.48	.46	.70	1.41	.50	.65	1.38	.55	.59
	3 " 4	1.79	.34	.71	1.75	.39	.70	1.71	.43	.68	1.63	.48	.63	1.59	.54	.59
	6 " 7	**2.29**	**.30**	**.68**	**2.24**	**.33**	**.70**	**2.17**	**.39**	**.64**	**2.08**	**.43**	**.62**	**2.03**	**.45**	**.54**
	8 " 10	3.03	.22	.54	3.01	.22	.58	2.93	.26	.56	2.90	.30	.56	2.88	.34	.51
¾ to 2 in.	½ to 1	1.47	.35	.80	1.44	.38	.79	1.40	.41	.77	1.34	.48	.71	1.29	.50	.67
	3 " 4	1.70	.33	.78	1.66	.37	.76	1.62	.38	.74	1.53	.43	.70	1.50	.49	.67
	6 " 7	**2.16**	**.29**	**.77**	**2.08**	**.34**	**.74**	**2.04**	**.33**	**.73**	**1.92**	**.37**	**.68**	**1.90**	**.42**	**.65**
	8 " 10	2.97	.22	.66	2.97	.22	.66	2.81	.25	.62	2.74	.28	.42	2.74	.23	.42
¾ to 3 in.	½ to 1	1.39	.33	.86	1.35	.36	.84	1.30	.38	.81	1.25	.42	.76	1.21	.46	.71
	3 " 4	1.60	.31	.83	1.55	.34	.83	1.52	.36	.81	1.46	.41	.78	1.42	.44	.73
	6 " 7	**2.03**	**.27**	**.78**	**1.98**	**.29**	**.76**	**1.94**	**.32**	**.75**	**1.87**	**.36**	**.72**	**1.83**	**.38**	**.70**
	8 " 10	2.87	.21	.68	2.85	.21	.67	2.75	.24	.69	2.69	.28	.68	2.64	.31	.66

Proportions for 3500 lb. per sq. in. Concrete

Based on 28-day compressive strength of 6 by 12-in. cylinders.

Mixing water, including moisture in aggregate, 4.7 gal. per sack of portland cement.

Proportions expressed in terms of dry and rodded volumes of aggregate.

Thus, 1-0.6-1.7 indicates 1 volume of cement, 0.6 volumes of fine aggregate and 1.7 of coarse aggregate.

No allowance made for bulking of aggregates due to moisture or loose measurement.

For precautions to be observed in using tables see page 9.

Size of Coarse Aggregate	Slump, in.	Proportions Using Fine Aggregate of Different Sizes				
		0-No. 30	0-No. 16	0-No. 8	0-No. 4	0-⅜ in.
None	½ to 1	1:1.2	1:1.4	1:1.6	1:1.9	1:2.2
	3 " 4	1:1.0	1:1.1	1:1.3	1:1.5	1:1.8
	6 " 7	**1:0.6**	**1:0.8**	**1:0.9**	**1:1.0**	**1:1.2**
	8 " 10	1:0.3	1:0.4	1:0.4	1:0.5	1:0.6
No. 4 to ¾ in.	½ to 1	1:1.0:2.2	1:1.1:2.2	1:1.3:2.1	1:1.5:2.0	1:1.8:1.8
	3 " 4	1:0.8:1.9	1:0.9:1.9	1:1.0:1.8	1:1.2:1.7	1:1.4:1.5
	6 " 7	**1:0.5:1.3**	**1:0.6:1.4**	**1:0.6:1.3**	**1:0.8:1.3**	**1:0.9:1.2**
	8 " 10	1:0.2:0.7	1:0.2:0.7	1:0.3:0.7	1:0.3:0.7	1:0.4:0.6
No. 4 to 1 in.	½ to 1	1:0.9:2.6	1:1.0:2.6	1:1.2:2.5	1:1.4:2.4	1:1.6:2.3
	3 " 4	1:0.7:2.2	1:0.8:2.2	1:0.9:2.2	1:1.1:2.1	1:1.3:2.0
	6 " 7	**1:0.4:1.5**	**1:0.5:1.5**	**1:0.6:1.5**	**1:0.6:1.5**	**1:0.8:1.4**
	8 " 10	1:0.2:0.8	1:0.2:0.8	1:0.2:0.8	1:0.3:0.8	1:0.3:0.8
No. 4 to 1½ in.	½ to 1	1:0.9:2.9	1:1.0:2.9	1:1.1:2.9	1:1.3:2.8	1:1.5:2.7
	3 " 4	1:0.7:2.5	1:0.8:2.4	1:0.9:2.4	1:1.0:2.4	1:1.2:2.3
	6 " 7	**1:0.4:1.8**	**1:0.5:1.7**	**1:0.5:1.8**	**1:0.6:1.7**	**1:0.7:1.7**
	8 " 10	1:0.2:0.9	1:0.2:0.9	1:0.2:0.9	1:0.2:0.9	1:0.3:0.9
No. 4 to 2 in.	½ to 1	1:0.7:3.3	1:0.8:3.3	1:0.9:3.4	1:1.0:3.3	1:1.2:3.3
	3 " 4	1:0.6:2.8	1:0.6:2.8	1:0.7:2.8	1:0.8:2.8	1:1.0:2.8
	6 " 7	**1:0.3:2.0**	**1:0.4:2.0**	**1:0.4:2.0**	**1:0.5:2.0**	**1:0.6:2.0**
	8 " 10	1:0.1:1.0	1:0.1:1.0	1:0.2:1.0	1:0.2:1.0	1:0.2:1.0
⅜ to 1 in.	½ to 1	1:1.1:2.5	1:1.2:2.5	1:1.4:2.5	1:1.6:2.3	1:1.8:2.2
	3 " 4	1:0.8:2.1	1:0.9:2.1	1:1.1:2.1	1:1.3:2.0	1:1.5:1.9
	6 " 7	**1:0.5:1.5**	**1:0.6:1.5**	**1:0.7:1.5**	**1:0.8:1.4**	**1:0.9:1.4**
	8 " 10	1:0.2:0.8	1:0.2:0.8	1:0.3:0.8	1:0.3:0.8	1:0.4:0.7
⅜ to 1½ in.	½ to 1	1:1.0:2.8	1:1.2:2.8	1:1.3:2.8	1:1.6:2.7	1:1.8:2.6
	3 " 4	1:0.8:2.4	1:0.9:2.4	1:1.1:2.4	1:1.2:2.3	1:1.5:2.3
	6 " 7	**1:0.5:1.7**	**1:0.6:1.7**	**1:0.7:1.7**	**1:0.8:1.7**	**1:0.9:1.6**
	8 " 10	1:0.2:0.8	1:0.2:0.8	1:0.3:0.8	1:0.3:0.8	1:0.4:0.8
⅜ to 2 in.	½ to 1	1:1.0:3.2	1:1.1:3.2	1:1.2:3.2	1:1.4:3.2	1:1.6:3.1
	3 " 4	1:0.8:2.7	1:0.8:2.7	1:1.0:2.7	1:1.1:2.7	1:1.3:2.7
	6 " 7	**1:0.5:1.9**	**1:0.5:1.9**	**1:0.6:2.0**	**1:0.7:2.0**	**1:0.8:1.9**
	8 " 10	1:0.2:0.9	1:0.2:1.0	1:0.2:1.0	1:0.3:1.0	1:0.3:1.0
¾ to 1½ in.	½ to 1	1:1.3:2.6	1:1.4:2.7	1:1.6:2.6	1:1.9:2.6	1:2.2:2.4
	3 " 4	1:1.0:2.2	1:1.2:2.3	1:1.3:2.2	1:1.5:2.2	1:1.8:2.1
	6 " 7	**1:0.7:1.6**	**1:0.7:1.6**	**1:0.9:1.6**	**1:1.0:1.6**	**1:1.2:1.6**
	8 " 10	1:0.3:0.8	1:0.3:0.8	1:0.4:0.8	1:0.4:0.8	1:0.5:0.8
¾ to 2 in.	½ to 1	1:1.2:3.0	1:1.4:3.1	1:1.6:3.1	1:1.8:3.1	1:2.1:3.0
	3 " 4	1:1.0:2.5	1:1.1:2.6	1:1.2:2.6	1:1.5:2.6	1:1.7:2.5
	6 " 7	**1:0.6:1.8**	**1:0.7:1.8**	**1:0.8:1.9**	**1:0.9:1.9**	**1:1.1:1.9**
	8 " 10	1:0.3:0.9	1:0.3:0.9	1:0.3:0.9	1:0.4:0.9	1:0.5:0.9
¾ to 3 in.	½ to 1	1:1.2:3.4	1:1.3:3.4	1:1.5:3.4	1:1.7:3.3	1:2.0:3.3
	3 " 4	1:1.0:2.8	1:1.1:2.8	1:1.2:2.8	1:1.4:2.8	1:1.6:2.8
	6 " 7	**1:0.6:2.0**	**1:0.7:2.0**	**1:0.8:2.0**	**1:0.9:2.0**	**1:1.0:2.0**
	8 " 10	1:0.3:1.0	1:0.3:1.0	1:0.3:1.0	1:0.4:1.0	1:0.4:1.0

Quantities of Materials for 1 cu. yd. of 3500 lb. per sq. in. Concrete

The volume of cement is expressed in barrels and of aggregates in cubic yards.

F = fine aggregate; C = coarse aggregate.

Quantities are net, no allowance being made for bulking or waste.

For precautions to be observed in using tables see page 9.

Size of Coarse Aggregate	Slump, in.	Quantities of Materials Using Fine Aggregate of Different Sizes											
		0-No. 30			0-No. 16			0-No. 8			0-No. 4			0-⅜ in.		
		Cement	Aggregate F.	Aggregate C.	Cement	Aggregate F.	Aggregate C.	Cement	Aggregate F.	Aggregate C.	Cement	Aggregate F.	Aggregate C.	Cement	Aggregate F.	Aggregate C.
None	½ to 1	3.58	.64		3.38	.70		3.11	.74		2.71	.76		2.48	.81	
	3 " 4	3.90	.58		3.83	.62		3.51	.68		3.13	.70		2.81	.75	
	6 " 7	**4.82**	**.43**		**4.34**	**.52**		**4.12**	**.55**		**3.79**	**.56**		**3.46**	**.61**	
	8 " 10				5.00	.30		4.95	.29		4.48	.33		4.37	.30	
No. 4 to ¾ in.	½ to 1	2.08	.31	.68	2.06	.34	.67	2.01	.39	.63	1.91	.42	.57	1.92	.51	.51
	3 " 4	2.38	.28	.67	2.36	.31	.66	2.52	.37	.67	2.25	.40	.57	2.22	.46	.49
	6 " 7	**3.08**	**.23**	**.59**	**3.02**	**.27**	**.63**	**2.96**	**.26**	**.57**	**2.88**	**.34**	**.56**	**2.83**	**.38**	**.50**
	8 " 10	4.02	.12	.42	3.96	.12	.41	3.89	.17	.40	3.83	.17	.40	3.79	.22	.34
No. 4 to 1 in.	½ to 1	1.95	.26	.75	1.93	.29	.74	1.90	.34	.70	1.84	.38	.65	1.84	.43	.63
	3 " 4	2.27	.24	.74	2.25	.27	.73	2.18	.29	.71	2.15	.35	.67	2.10	.40	.62
	6 " 7	**2.93**	**.17**	**.65**	**2.89**	**.21**	**.64**	**2.79**	**.25**	**.62**	**2.74**	**.24**	**.61**	**2.67**	**.32**	**.55**
	8 " 10	3.88	.11	.46	3.82	.11	.45	3.79	.11	.45	3.68	.16	.44	3.67	.16	.43
No. 4 to 1½ in.	½ to 1	1.85	.25	.79	1.85	.27	.79	1.80	.29	.77	1.70	.33	.70	1.73	.38	.69
	3 " 4	2.14	.22	.79	2.11	.25	.75	2.05	.27	.73	1.97	.29	.70	1.98	.35	.67
	6 " 7	**2.76**	**.22**	**.74**	**2.70**	**.20**	**.68**	**2.59**	**.19**	**.69**	**2.58**	**.23**	**.65**	**2.58**	**.27**	**.65**
	8 " 10	3.79	.11	.50	3.69	.11	.49	3.67	.11	.49	3.72	.11	.50	3.80	.17	.51
No. 4 to 2 in.	½ to 1	1.79	.19	.87	1.77	.21	.86	1.71	.23	.86	1.68	.25	.87	1.65	.29	.81
	3 " 4	2.04	.18	.84	2.00	.18	.83	1.95	.20	.81	1.92	.23	.80	1.91	.28	.79
	6 " 7	**2.62**	**.12**	**.78**	**2.60**	**.15**	**.77**	**2.52**	**.15**	**.75**	**2.50**	**.19**	**.74**	**2.50**	**.22**	**.74**
	8 " 10	3.81	.06	.56	3.75	.06	.56	3.72	.11	.55	3.68	.11	.54	3.76	.11	.56
⅜ to 1 in.	½ to 1	2.02	.33	.75	1.94	.34	.72	1.88	.39	.69	1.85	.44	.63	1.79	.48	.58
	3 " 4	2.28	.27	.71	2.24	.30	.70	2.18	.35	.68	2.14	.41	.63	2.05	.45	.58
	6 " 7	**2.86**	**.21**	**.64**	**2.84**	**.25**	**.63**	**2.76**	**.29**	**.61**	**2.74**	**.32**	**.57**	**2.66**	**.35**	**.55**
	8 " 10	3.88	.11	.46	3.82	.11	.45	3.79	.17	.45	3.68	.16	.44	3.67	.22	.38
⅜ to 1½ in.	½ to 1	1.88	.28	.78	1.85	.33	.77	1.79	.34	.74	1.74	.41	.70	1.69	.45	.65
	3 " 4	2.16	.26	.77	2.10	.28	.75	2.04	.33	.73	1.98	.35	.67	1.93	.43	.66
	6 " 7	**2.72**	**.20**	**.68**	**2.66**	**.24**	**.67**	**2.59**	**.27**	**.65**	**2.56**	**.30**	**.64**	**2.52**	**.34**	**.60**
	8 " 10	3.79	.11	.45	3.69	.11	.44	3.67	.16	.43	3.40	.15	.40	3.31	.20	.39
⅜ to 2 in.	½ to 1	1.78	.26	.84	1.75	.28	.83	1.69	.30	.80	1.63	.36	.77	1.59	.38	.73
	3 " 4	2.03	.24	.81	1.98	.23	.79	1.93	.29	.77	1.91	.31	.76	1.84	.35	.73
	6 " 7	**2.58**	**.19**	**.73**	**2.54**	**.19**	**.71**	**2.49**	**.22**	**.74**	**2.47**	**.26**	**.73**	**2.40**	**.28**	**.68**
	8 " 10	3.80	.11	.51	3.73	.11	.55	3.64	.11	.54	3.68	.16	.54	3.56	.16	.53
¾ to 1½ in.	½ to 1	1.84	.35	.71	1.82	.38	.73	1.77	.42	.68	1.68	.47	.65	1.65	.54	.59
	3 " 4	2.13	.32	.69	2.09	.37	.71	2.02	.39	.66	1.85	.41	.60	1.89	.50	.59
	6 " 7	**2.68**	**.28**	**.64**	**2.63**	**.27**	**.62**	**2.56**	**.34**	**.61**	**2.49**	**.37**	**.59**	**2.45**	**.44**	**.58**
	8 " 10	3.79	.17	.45	3.69	.16	.43	3.67	.22	.43	3.72	.22	.44	3.66	.27	.43
¾ to 2 in.	½ to 1	1.76	.31	.78	1.72	.36	.79	1.67	.40	.77	1.58	.42	.72	1.55	.48	.69
	3 " 4	2.01	.30	.74	1.95	.31	.75	1.92	.34	.74	1.84	.41	.71	1.80	.45	.67
	6 " 7	**2.58**	**.23**	**.69**	**2.54**	**.26**	**.68**	**2.48**	**.29**	**.70**	**2.40**	**.32**	**.68**	**2.35**	**.38**	**.66**
	8 " 10	3.78	.17	.50	3.73	.17	.50	3.63	.16	.48	3.59	.21	.48	3.49	.26	.46
¾ to 3 in.	½ to 1	1.67	.30	.84	1.61	.31	.81	1.57	.35	.79	1.51	.38	.74	1.47	.43	.72
	3 " 4	1.91	.28	.79	1.86	.30	.77	1.93	.34	.80	1.76	.36	.73	1.71	.40	.71
	6 " 7	**2.48**	**.22**	**.74**	**2.43**	**.25**	**.72**	**2.37**	**.28**	**.70**	**2.30**	**.31**	**.68**	**2.25**	**.33**	**.67**
	8 " 10	3.64	.16	.54	3.57	.16	.53	3.52	.16	.52	3.46	.20	.51	3.38	.20	.50

Proportions for 4000 lb. per sq. in. Concrete

Based on 28-day compressive strength of 6 by 12-in. cylinders.

Mixing water, including moisture in aggregate, 4.2 gal. per sack of portland cement.

Proportions expressed in terms of dry and rodded volumes of aggregate.

Thus, 1-0.4-1.2 indicates 1 volume of cement, 0.4 volumes of fine aggregate and 1.2 of coarse aggregate.

No allowance made for bulking of aggregates due to moisture or loose measurement.

For precautions to be observed in using tables see page 9.

Size of Coarse Aggregate	Slump, in.	Proportions Using Fine Aggregate of Different Sizes				
		0-No. 30	0-No. 16	0-No. 8	0-No. 4	0-⅜ in.
None	½ to 1	1:0.9	1:1.1	1:1.2	1:1.5	1:1.7
	3 " 4	1:0.7	1:0.9	1:1.0	1:1.2	1:1.4
	6 " 7	**1:0.4**	**1:0.5**	**1:0.6**	**1:0.7**	**1:0.7**
	8 " 10	1:0.1	1:0.2	1:0.2	1:0.2	1:0.3
No. 4 to ¾ in.	½ to 1	1:0.8:1.8	1:0.9:1.8	1:1.0:1.8	1:1.2:1.7	1:1.4:1.5
	3 " 4	1:0.6:1.5	1:0.6:1.4	1:0.8:1.5	1:0.9:1.4	1:1.1:1.3
	6 " 7	**1:0.3:0.9**	**1:0.4:1.0**	**1:0.4:0.9**	**1:0.5:0.9**	**1:0.6:0.9**
	8 " 10	1:0.1:0.3	1:0.1:0.3	1:0.1:0.3	1:0.1:0.3	1:0.2:0.3
No. 4 to 1 in.	½ to 1	1:0.7:2.1	1:0.8:2.1	1:0.9:2.1	1:1.0:2.0	1:1.2:1.9
	3 " 4	1:0.5:1.7	1:0.6:1.6	1:0.7:1.7	1:0.8:1.7	1:0.9:1.6
	6 " 7	**1:0.3:1.1**	**1:0.3:1.1**	**1:0.4:1.1**	**1:0.4:1.1**	**1:0.5:1.1**
	8 " 10	1:0.1:0.4	1:0.1:0.4	1:0.1:0.4	1:0.1:0.4	1:0.1:0.4
No. 4 to 1½ in.	½ to 1	1:0.6:2.4	1:0.7:2.4	1:0.8:2.4	1:1.0:2.3	1:1.1:2.2
	3 " 4	1:0.5:2.0	1:0.5:1.9	1:0.6:2.0	1:0.7:1.9	1:0.9:1.9
	6 " 7	**1:0.3:1.2**	**1:0.3:1.2**	**1:0.3:1.2**	**1:0.4:1.2**	**1:0.4:1.2**
	8 " 10	1:0.1:0.4	1:0.1:0.4	1:0.1:0.4	1:0.1:0.4	1:0.1:0.4
No. 4 to 2 in.	½ to 1	1:0.5:2.7	1:0.6:2.7	1:0.7:2.7	1:0.8:2.7	1:0.9:2.5
	3 " 4	1:0.4:2.2	1:0.4:2.2	1:0.5:2.3	1:0.6:2.3	1:0.7:2.3
	6 " 7	**1:0.2:1.4**	**1:0.2:1.4**	**1:0.3:1.4**	**1:0.3:1.5**	**1:0.3:1.4**
	8 " 10	1:0.1:0.4	1:0.1:0.4	1:0.1:0.5	1:0.1:0.5	1:0.1:0.5
⅜ to 1 in.	½ to 1	1:0.8:2.1	1:0.9:2.0	1:1.0:2.0	1:1.2:1.9	1:1.4:1.8
	3 " 4	1:0.6:1.7	1:0.7:1.7	1:0.8:1.6	1:0.9:1.6	1:1.1:1.5
	6 " 7	**1:0.3:1.1**	**1:0.4:1.1**	**1:0.4:1.0**	**1:0.5:1.0**	**1:0.6:1.0**
	8 " 10	1:0.1:0.4	1:0.1:0.4	1:0.1:0.4	1:0.1:0.4	1:0.2:0.4
⅜ to 1½ in.	½ to 1	1:0.8:2.3	1:0.9:2.3	1:1.0:2.3	1:1.2:2.3	1:1.4:2.2
	3 " 4	1:0.6:1.9	1:0.7:1.9	1:0.8:1.9	1:0.9:1.9	1:1.1:1.8
	6 " 7	**1:0.3:1.2**	**1:0.4:1.2**	**1:0.4:1.2**	**1:0.5:1.2**	**1:0.6:1.3**
	8 " 10	1:0.1:0.4	1:0.1:0.4	1:0.1:0.4	1:0.1:0.4	1:0.2:0.4
⅜ to 2 in.	½ to 1	1:0.7:2.6	1:0.8:2.6	1:0.9:2.6	1:1.0:2.6	1:1.2:2.4
	3 " 4	1:0.6:2.1	1:0.6:2.2	1:0.7:2.2	1:0.8:2.2	1:1.0:2.2
	6 " 7	**1:0.3:1.4**	**1:0.3:1.4**	**1:0.4:1.4**	**1:0.4:1.4**	**1:0.5:1.4**
	8 " 10	1:0.1:0.4	1:0.1:0.4	1:0.1:0.5	1:0.1:0.4	1:0.1:0.5
¾ to 1½ in.	½ to 1	1:1.0:2.2	1:1.1:2.2	1:1.3:2.2	1:1.5:2.1	1:1.7:2.0
	3 " 4	1:0.8:1.8	1:0.9:1.8	1:1.0:1.8	1:1.2:1.8	1:1.3:1.7
	6 " 7	**1:0.4:1.1**	**1:0.5:1.1**	**1:0.6:1.2**	**1:0.7:1.1**	**1:0.8:1.1**
	8 " 10	1:0.1:0.4	1:0.1:0.4	1:0.2:0.4	1:0.2:0.4	1:0.2:0.4
¾ to 2 in.	½ to 1	1:0.9:2.5	1:1.0:2.5	1:1.2:2.5	1:1.4:2.5	1:1.6:2.3
	3 " 4	1:0.7:2.0	1:0.8:2.1	1:0.9:2.1	1:1.1:2.1	1:1.3:2.0
	6 " 7	**1:0.4:1.3**	**1:0.5:1.3**	**1:0.5:1.4**	**1:0.6:1.4**	**1:0.7:1.4**
	8 " 10	1:0.1:0.4	1:0.1:0.4	1:0.2:0.4	1:0.2:0.4	1:0.2:0.4
¾ to 3 in.	½ to 1	1:0.9:2.7	1:1.0:2.7	1:1.2:2.8	1:1.3:2.7	1:1.5:2.7
	3 " 4	1:0.7:2.2	1:0.8:2.3	1:0.9:2.3	1:1.0:2.3	1:1.2:2.2
	6 " 7	**1:0.4:1.4**	**1:0.4:1.4**	**1:0.5:1.5**	**1:0.6:1.5**	**1:0.7:1.5**
	8 " 10	1:0.1:0.5	1:0.1:0.5	1:0.1:0.5	1:0.2:0.5	1:0.2:0.5

Quantities of Materials for 1 cu. yd. of 4000 lb. per sq. in. Concrete

The volume of cement is expressed in barrels and of aggregates in cubic yards.

F = fine aggregate; C = coarse aggregate.

Quantities are net, no allowance being made for bulking or waste.

For precautions to be observed in using tables see page 9.

Size of Coarse Aggregate	Slump, in.	Quantities of Materials Using Fine Aggregate of Different Sizes											
		0-No. 30			0-No. 16			0-No. 8			0-No. 4			0-⅜ in.		
		Cement	Aggregate F.	C.	Cement	Aggregate F.	C.	Cement	Aggregate F.	C.	Cement	Aggregate F.	C.	Cement	Aggregate F	C.
None	½ to 1	4.21	.56		3.91	.65		3.75	.79		3.19	.71		2.96	.75	
	3 " 4	4.64	.48		4.25	.57		4.03	.60		3.57	.64		3.27	.68	
	6 " 7	**5.05**	**.30**		**5.21**	**.39**		**4.89**	**.44**		**4.36**	**.45**		**4.41**	**.46**	
	8 " 10													4.78	.21	
No. 4 to ¾ in.	½ to 1	2.46	.29	.65	2.44	.32	.65	2.39	.35	.64	2.33	.41	.59	2.30	.48	.51
	3 " 4	2.86	.25	.64	2.80	.25	.58	2.74	.32	.61	2.64	.35	.55	2.61	.42	.50
	6 " 7	**3.68**	**.16**	**.49**	**3.67**	**.22**	**.54**	**3.62**	**.21**	**.48**	**3.56**	**.26**	**.48**	**3.54**	**.23**	**.34**
	8 " 10	4.79	.06	.23	4.79	.07	.23	4.77	.08	.23	4.76	.10	.23	4.74	.11	.22
No. 4 to 1 in.	½ to 1	2.36	.24	.73	2.32	.27	.72	2.27	.30	.71	2.21	.33	.65	2.18	.39	.61
	3 " 4	2.71	.20	.68	2.65	.24	.63	2.58	.27	.65	2.56	.30	.64	2.54	.34	.60
	6 " 7	**3.59**	**.16**	**.58**	**3.58**	**.16**	**.58**	**3.51**	**.21**	**.57**	**3.46**	**.20**	**.56**	**3.48**	**.26**	**.57**
	8 " 10	4.79	.05	.25	4.76	.05	.26	4.73	.07	.26	4.70	.08	.26	4.69	.09	.26
No. 4 to 1½ in.	½ to 1	2.25	.20	.80	2.21	.23	.78	2.15	.25	.76	2.03	.30	.69	2.05	.33	.67
	3 " 4	2.56	.19	.76	2.54	.19	.71	2.46	.22	.73	2.43	.25	.68	2.42	.32	.68
	6 " 7	**3.48**	**.15**	**.62**	**3.47**	**.15**	**.62**	**3.39**	**.15**	**.60**	**3.34**	**.20**	**.59**	**3.34**	**.20**	**.59**
	8 " 10	4.69	.04	.28	4.69	.05	.28	4.69	.06	.29	4.67	.07	.29	4.67	.08	.29
No. 4 to 2 in.	½ to 1	2.14	.16	.86	2.10	.19	.84	2.03	.21	.81	2.00	.24	.80	1.91	.26	.79
	3 " 4	2.47	.15	.80	2.45	.15	.80	2.37	.18	.81	2.33	.21	.79	2.31	.24	.78
	6 " 7	**3.36**	**.10**	**.70**	**3.33**	**.10**	**.69**	**3.24**	**.14**	**.67**	**3.19**	**.14**	**.71**	**3.20**	**.14**	**.66**
	8 " 10	4.69	.03	.31	4.68	.03	.30	4.67	.04	.32	4.61	.04	.33	4.54	.05	.33
⅜ to 1 in.	½ to 1	2.36	.29	.73	2.32	.31	.69	2.26	.33	.67	2.22	.39	.62	2.13	.44	.57
	3 " 4	2.65	.24	.67	2.62	.27	.66	2.58	.31	.61	2.54	.34	.60	2.48	.40	.55
	6 " 7	**3.42**	**.15**	**.56**	**3.39**	**.20**	**.55**	**3.33**	**.20**	**.49**	**3.30**	**.24**	**.49**	**3.23**	**.29**	**.48**
	8 " 10	4.79	.06	.26	4.76	.07	.25	4.73	.08	.26	4.70	.10	.25	4.69	.12	.24
⅜ to 1½ in.	½ to 1	2.26	.27	.77	2.20	.29	.75	2.14	.32	.73	2.08	.37	.71	2.00	.41	.65
	3 " 4	2.54	.23	.71	2.51	.26	.71	2.48	.29	.70	2.42	.32	.68	2.36	.38	.63
	6 " 7	**3.24**	**.14**	**.58**	**3.17**	**.19**	**.56**	**3.16**	**.19**	**.56**	**3.10**	**.23**	**.55**	**3.13**	**.28**	**.56**
	8 " 10	4.69	.06	.28	4.69	.07	.28	4.69	.08	.28	4.67	.09	.28	4.67	.11	.28
⅜ to 2 in.	½ to 1	2.14	.22	.82	2.08	.25	.80	2.01	.27	.77	1.98	.29	.76	1.92	.34	.74
	3 " 4	2.46	.22	.76	2.42	.21	.79	2.34	.24	.76	2.31	.27	.75	2.22	.33	.72
	6 " 7	**3.14**	**.14**	**.65**	**3.07**	**.14**	**.64**	**3.02**	**.18**	**.63**	**3.02**	**.18**	**.63**	**2.98**	**.22**	**.62**
	8 " 10	4.69	.05	.30	4.68	.06	.30	4.67	.07	.32	4.61	.08	.31	4.54	.08	.31
¾ to 1½ in.	½ to 1	2.23	.33	.72	2.18	.35	.71	2.12	.41	.69	2.01	.45	.62	1.95	.49	.58
	3 " 4	2.53	.30	.68	2.49	.33	.66	2.44	.36	.65	2.42	.43	.65	2.29	.44	.58
	6 " 7	**3.18**	**.19**	**.52**	**3.12**	**.23**	**.51**	**3.03**	**.27**	**.54**	**2.97**	**.31**	**.48**	**2.98**	**.35**	**.49**
	8 " 10	4.69	.08	.26	4.69	.10	.27	4.69	.11	.28	4.67	.12	.28	4.67	.15	.27
¾ to 2 in.	½ to 1	2.11	.28	.78	2.05	.30	.76	1.99	.35	.74	1.91	.40	.71	1.88	.44	.69
	3 " 4	2.44	.25	.72	2.39	.28	.74	2.34	.31	.73	2.24	.36	.70	2.18	.42	.68
	6 " 7	**3.12**	**.18**	**.60**	**3.11**	**.23**	**.60**	**3.00**	**.22**	**.62**	**2.94**	**.26**	**.61**	**2.90**	**.30**	**.56**
	8 " 10	4.69	.08	.29	4.68	.09	.30	4.67	.10	.30	4.61	.11	.30	4.54	.13	.30
¾ to 3 in.	½ to 1	1.98	.25	.79	1.94	.29	.77	1.90	.34	.79	1.84	.35	.74	1.78	.40	.71
	3 " 4	2.33	.24	.76	2.28	.27	.78	2.21	.30	.75	2.12	.31	.72	2.06	.37	.67
	6 " 7	**3.00**	**.18**	**.62**	**2.97**	**.18**	**.62**	**2.96**	**.22**	**.66**	**2.90**	**.26**	**.64**	**2.77**	**.29**	**.62**
	8 " 10	4.60	.08	.32	4.54	.08	.32	4.49	.09	.32	4.44	.10	.32	4.43	.12	.32

CALCULATION OF QUANTITIES FOR CONDITIONS NOT COVERED BY TABLES

The proportions for aggregate sizes, slumps and concrete strengths not given in the tables, but falling within the range covered, can, in general, be computed by linear interpolation. In other words, for the narrow range between adjacent values, a straight-line relation may be considered to exist between strength and size of aggregate, slump, and quantity of cement.

The following examples illustrate the methods of interpolation. All proportions are in terms of dry and rodded volumes.

Calculate Proportions for 2300-lb. Concrete.

Assume slump of 6 to 7 in., sand 0-No. 4, coarse aggregate No. 4-1½ in.

Proportions for 2000-lb. concrete	1:1.7:3.4
" " 2500-lb. "	1:1.3:2.8
Difference	0:0.4:0.6
2/5 difference (to be added to 2500-lb.)	0:0.2:0.2
Proportions for 2300-lb. concrete	1:1.5:3.0

The same result will be obtained by subtracting 3/5 of the difference from the 2000-lb. proportions.

Calculate Proportions for 5 to 6-in. Slump.

Assume 2500-lb. concrete, sand 0-No. 4 and coarse aggregate No. 4-1½ in.

Proportions for 3 to 4-in. slump (av. 3.5 in.)	1:1.8:3.5
" " 6 to 7-in. " (av. 6.5 in.)	1:1.3:2.8
Difference	0:0.5:0.7
1/3 of difference	0:0.2:0.2

(The difference between 6 to 7-in. and 5 to 6-in. slump is 1/3 the difference between 6 to 7 in. and 3 to 4 in.)

Proportions for 5 to 6-in. slump (av. 5.5 in.)	1:1.5:3.0

Calculate Proportions for ¾ to 2½-in. Aggregate.

Assume 3000-lb. concrete, slump 3 to 4 in., and sand 0-No. 4.

Proportions for ¾-3-in. aggregate	1:1.9:3.6
" " ¾-2-in. "	1:1.9:3.1
Difference	0:0.0:0.5
½ of difference (to be added to ¾-2-in.)	0:0.0:0.2
Proportions for ¾-2½-in. aggregate	1:1.9:3.3

Calculate Proportions for No. 4 to 3-in. Aggregate.

Assume 3000-lb. concrete, slump 3 to 4 in., and sand 0-No. 4.

		Differences
Proportions for No. 4- ¾-in	1:1.6:2.0	
" " No. 4-1 -in	1:1.4:2.5	0:—0.2:+0.5
" " No. 4-1½-in	1:1.4:2.9	0:—0.0:+0.4
" " No. 4-2 -in	1:1.1:3.4	0:—0.3:+0.5
Average		0:—0.2:+0.5
Proportions for No. 4-2-in	1: 1.1: 3.4	
Average difference	0:—0.2:+0.5	
Proportions for No. 4-3-in	1: 0.9: 3.9	

APPENDIX 1

TEST METHODS

When proportioning concrete on the basis of these tables, the sampling of aggregate, the determination of cleanness, maximum size and bulking due to moisture, and the making of control tests, should be done in accordance with standard methods. The principal features of the methods to be followed are described below.

Standard methods of the A.S.T.M. are given wherever applicable.

Sampling of Aggregates—In selecting samples of aggregate for test it is of utmost importance that the samples be *representative*. Samples for sieve analysis may be selected by "quartering" or by the use of a sampler. For fine aggregate, a sample of 500 grams (about 1 lb.) or more should be used. The weight in grams of the coarse aggregate sample should be not less than 3000 times the maximum size of particle measured in inches.

Cleanness of Aggregates—The "colorimetric test" for organic impurities in sands[8] may be made by thoroughly shaking a sample in a 3% solution of sodium hydroxide, allowing it to stand for 24 hours, and observing the color of the liquid. A dark color indicates the presence of such quantities of organic impurities that the sand should be rejected unless mortar strength tests show it to be satisfactory.

Silt may be determined in accordance with the "Tentative Method of Decantation Test for Sand and Other Fine Aggregates" of the A.S.T.M. In general, fine aggregate should not contain more than 3% of silt by weight (about 5% by volume).

The quantity of shale in coarse aggregates may be determined by the method of flotation on zinc chloride. For sands, the most accurate method is to sort the shale particles by hand.[9]

Size of Aggregate—The size to be assigned to an aggregate is determined from the sieve analysis by applying the following rules:

1. 15% or more shall be retained on the sieve next smaller than that considered the maximum size.[10]

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[8]See "Abrams-Harder Field Test for Organic Impurities in Sands," Proc. Am. Soc. Testing Mat., 1919; Part I, "Standard Method of Test for Organic Impurities in Sands for Concrete" (Serial Designation C40-22), Am. Soc. Testing Mat. Standards, 1924.

[9]See "Tentative Standard Methods of Sampling and Testing Highway Materials," Bull. 1216, U. S. Dept. of Agriculture, 1924, for a method of determining the amount of shale in aggregate.

[10]A graded sand with 16% retained on the No. 8 sieve would fall in the 0-No. 4 size; if 14% or less were retained, the sand would fall in the 0-No. 8 size. A coarse aggregate having 16% coarser than the 2-in. sieve and less than 15% coarser than the 3-in. sieve would be considered as 3-in. aggregate.

2. Not more than 15% of a given coarse aggregate shall be finer than the sieve considered as the minimum size.

3. Only the sieve sizes given in the following table shall be considered in applying Rules 1 and 2.

Sieve Analysis of Aggregate—The sieve analysis should be made in accordance with the "Tentative Method of Test for Sieve Analysis of Aggregate for Concrete" of the A.S.T.M. The test is made by determining the cumulative percentages coarser than each of the following sieves:

SIEVES FOR AGGREGATE TESTS

Square-mesh, woven-wire sieves may be obtained from The W. S. Tyler Co., Cleveland, Ohio.

Sieve Number or Size	Size of Clear Opening Inches
100	0.0059
50*	0.0117
30*	0.0232
16*	0.0469
8	0.094
4	0.187
⅜-in.	0.375
¾-in.	0.75
1 -in.†	1.00
1½-in.	1.50
2 -in.†	2.00
3 -in.	3.00

*Sieves No. 50, 30 and 16 are identical with No. 48, 28 and 14 used in earlier reports of this Laboratory.

†The 1- and 2-in. sieves are "half-size" sieves and are not used in calculating the *fineness modulus* of aggregates. The fineness modulus (used as a measure of the size and grading of an aggregate) is the summation of the percentages in the sieve analysis when expressed as cumulative percentages *coarser* than each sieve, divided by 100. (See Bulletin 1—"Design of Concrete Mixtures.")

It will be noted that, if the half sizes are omitted, each sieve has a clear opening double that of the next smaller.

Field tests may be made with sufficient accuracy by using alternate sieves in the standard set; the 50, 16, 4 and ¾-in. sieves have been found convenient for this purpose. The percentages for the omitted sieves may be determined by interpolation, after plotting a sieve analysis curve.

Moisture Content and Bulking—The moisture content and bulking of an aggregate may be determined as follows: Fill a convenient measure having vertical sides with the aggregate in such a way that job conditions are duplicated as nearly as practicable, strike off and weigh. Dry and weigh the entire sample. Replace the dried sample in the vessel in three layers, rodding each layer 25 to 30 times with a ⅝-in. round rod pointed at the lower end, level and measure the depth of aggregate in vessel. The percentage of bulking and moisture content

may now be calculated. Suppose a vessel 11 in. deep holds 18 lb. of moist sand and that on drying and rodding, the sand weighs 17 lb. and fills the vessel to a depth of 8¾ in.

The moisture content is $\frac{18-17}{17} = \frac{1}{17} = 0.059 = 5.9\%$

The bulking of the sand is $\frac{11-8.75}{8.75} = \frac{2.25}{8.75} = 0.26 = 26\%$.

The troublesome effects of the bulking of sands due to moisture may be eliminated by measurement inundated with water.[11]

Slump Test—The slump is the change in height, upon removal of the form, of a truncated cone of freshly-deposited concrete having a height of 12 in., top diameter 4 in., and bottom diameter 8 in. The newly-mixed concrete is lightly tamped into the mold in three layers using a metal rod ⅝ in. in diameter. After filling, the mold is immediately removed and the slump or settlement of the concrete measured. (See A.S.T.M. "Standard Method of Test for Consistency of Portland-Cement Concrete.")

Flow Test—The apparatus[12] for making the flow test for plasticity or workability consists of a metal table attached to a base in such a way that it can be raised by means of a cam and dropped by gravity. The concrete is molded into a truncated cone 5 in. high, top diameter 6¾ in., and bottom diameter 10 in. The test is made by placing the mold on the metal table of the machine and lightly puddling the freshly-mixed concrete into place with a ⅝-in. round hard rubber rod.[13] After being filled, the mold is immediately withdrawn and the table raised and dropped ½ in. 15 times in about 10 seconds. The base diameter of the mass of concrete after test, expressed as a percentage of the original base diameter is the "flow."

Comparison of Slump and Flow—For average conditions concrete having a slump of 3 to 4 in. requires about 10% more water than one having a slump of ½ to 1 in.; 6 to 7 in., 25% more; and 8 to 10 in., 50% more than for ½ to 1-in. slump. Concrete having a slump of ½ to 1 in. will give a flow of about 140 to 160; 3 to 4-in. slump, a flow of 180 to 200; 6 to 7-in. slump, a flow of 210 to 230; 8 to 10-in. slump, a flow of 230 to 250.

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[11]See "Method for Measuring Sands in Inundated Condition," by R. L. Bertin; Proc. Am. Soc. Testing Mat., v. 22, 1922, p. 404. "Inundation Methods for Measurements of Sand in Making Concrete," by Smith and Slater; Proc. Am. Concrete Inst., v. 19, 1923, p. 222. "Applying the Inundation Method to Control Moisture Content," by A. A. Levison; Proc. Am. Concrete Institute, 1925.

[12]A hard rubber or wooden rod is used in order to avoid marring the smooth top of the bronze or brass table.

[13]One design of the flow table is described in Proc. Am. Soc. Testing Mat., v. 20, Part II, 1920, p. 242 and in Concrete, June, 1920, p. 274.

Sampling Concrete—Samples of concrete for use in molding test specimens in the field should be taken at the mixer, at the ends of chutes, etc., or immediately after it has been placed in the work. The concrete for each specimen should be taken from one place, and a sufficient number of samples taken at different places to give an average of the concrete placed in that part of the work.

Molding Concrete Specimens for Compression Test—The specimens should be made in cylindrical metal forms having height equal to twice the diameter (usually 6 by 12 in.). The concrete should be puddled into the molds in three equal layers by means of a $\frac{5}{8}$-in. round rod pointed at the lower end. The specimens should be set squarely on a level base, and the tops should be finished smooth.

Capping—The ends of the test cylinders should be plane and as near parallel as practicable, to insure an equal distribution of the load over the section. Following are two methods of capping:

a. *Capped when molded*—Mold the cylinders on machined metal plates and cap the tops with retempered neat cement paste 4 to 5 hours later. The tops should be made plane by means of plate glass or a machined metal plate. The purpose of retempering the cement is to minimize volume changes during setting.

b. *Capped at time of test*—Cap both ends of the cylinder with a thin layer of paste made up of a mixture of equal parts of portland cement and plaster of paris. The caps should be made plane by means of plate glass or a machined metal surface. The caps should be allowed to harden 4 hours or more before the cylinders are tested.

Curing Test Cylinders—About 48 hours after molding, the concrete cylinders should be removed from the forms and cured in a moist place at a temperature of about 65 to 75° F. Field specimens should be shipped to the laboratory about 10 days prior to test and again cured in a moist place. The specimens should be kept moist during shipment.

Age at Test—In general, the specimens should be tested in a damp condition at the age of 28 days. If tests at other ages are desired, 3 and 7 days, 3 months and 1 year are recommended.

Testing—A bearing block with a spherical socket should be used on top of the cylinders.

Laboratory Tests of Concrete—Concrete tests carried out for the determination of proportions to be used in the work should be made in accordance with "Tentative Methods of Making Compression Tests of Concrete" of the A.S.T.M. Most of the tests are described above.

APPENDIX 2

FIELD TESTS OF CONCRETE

Since the development of accurate methods for designing concrete proportions and the standardization of test methods, considerable interest has been displayed by engineers and builders in the application of these methods to field work. The work of the Hydro-Electric Power Commission of Ontario,[14] the design of the concrete proportions for a large reinforced concrete bridge constructed at Sidney, Ohio, by the Big Four Railroad[15] and the control of the concrete for Becks Run Bridge at Pittsburgh by the Pennsylvania Railroad,[16] are three of several striking examples of the present-day trend toward making concrete of known strength.

Tests were made in 1923 during construction on 7 reinforced concrete jobs in the vicinity of New York City and Philadelphia[17] for the purpose of determining the feasibility of specifying concrete on the basis of strength. These tests were made through the cooperation of the Joint Committee on Standard Specifications for Concrete and Reinforced Concrete, the U. S. Bureau of Standards, the Associated General Contractors, the New York Group of Contractors, and this Laboratory. The tests showed that it is feasible to produce concrete of specified strength if careful control is exercised and if reasonable tolerances are permitted. Of the several hundred 6 by 12-in. concrete cylinders tested, about 90 per cent gave strengths greater than 80 per cent of the average; the averages for the different jobs were generally within 10 to 15 per cent of the predicted strength (usually higher).

One of the most important results of the growing practice of controlling the quality of concrete by tests has been the impetus given to the development of better equipment for measuring aggregates. Batch

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[14]Proportioning Concrete on Job by Exact Methods, by Young and McCarthy; Eng. News-Record, March 17, 1921. New methods for Proportioning Concrete, by Young and McCarthy; Canadian Eng., v. 9, p. 263, 1922.

[15]Old and New Methods of Constructing Concrete Bridges, by J. B. Hunley; Proc. Am. Concrete Inst., 1924; Eng. and Contr., March 26, April 23 and May 28, 1924.

[16]Design of Concrete Mixtures under Field Conditions, by T. P. Watson; Proc. Am. Concrete Inst., v. 21, 1925.

[17]Field Tests of Concrete Used on Construction Work, by Slater and Walker; Proc. Am. Concrete Inst., v. 20, 1924, p. 420. Field Tests of Concrete, by Ahlers and Walker; Proc. Am. Concrete Inst., v. 20, 1924, p. 358. Report to Joint Committee on Field Tests of Concrete Used on Construction Work, by Slater and Walker; Proc. Am. Soc. Civil Eng., January, 1925.

hoppers provided with "strike-off" gates, the "inundator"[18] and scales[19] for weighing aggregates, illustrate the trend in the direction of more accurate measurements.

Hoppers provided with strike-off gates have been in use in one form or another for several years. They may be set to furnish accurately measured volumes, and add greatly to the uniformity of the concrete if proper corrections are made for bulking of aggregates.

The "inundator" is a device for measuring sand saturated with water. This method eliminates the bulking due to moisture and loose measurement.

In recent years, concrete has been successfully proportioned by weight on a number of important jobs. The advantages of this method in maintaining uniformity of proportions are obvious.

If the sand is measured by weight, 5 per cent of moisture introduces a maximum error of 5 per cent in the quantity of material; if the measurements are made by volume the error may be 5 times this amount, if no correction is made for bulking. It should be pointed out, however, that satisfactory accuracy can be maintained by the use of volumetric measurements, if the equipment is properly used and corrections are made for bulking due to moisture and loose measurement.

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[18]See footnote 11, page 23.

[19]Weighing Aggregates for Concrete Highway Pavement, by R. W. Crum; Proc. Am. Concrete Inst., 1924. Experiences of Iowa Highway Commission; Eng. and Contr., v. 61, p. 730, April 2, 1924.

Bulletin 10
Structural Materials Research Laboratory
Lewis Institute
Chicago

Wear Tests of Concrete

By

DUFF A. ABRAMS

Professor in Charge of Laboratory

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FOREWORD

This paper was originally published in the copyrighted *Proceedings* of the American Society for Testing Materials, Vol. 21, 1921. The discussions which appear in the *Proceedings* have been omitted; a summary has been added which was omitted in the original publication.

Acknowledgment is made to the Society for permission to reprint the paper in bulletin form.

The results of certain wear tests of concrete made in this Laboratory have already been published in the following papers:

A Method of Making Wear Tests of Concrete; Proc. Am. Soc. Testing Mats., Part 2, 1916.

Effect of Time of Mixing on the Strength and Wear of Concrete; Proc. Am. Concrete Inst., 1918.

Effect of Curing Condition on the Wear and Strength of Concrete; Proc. Am. Railway Eng. Assn., Vol. 20, 1919; reprinted as Bulletin 2 of this Laboratory.

Effect of Hydrated Lime and Other Powdered Admixtures in Concrete; Proc. Am. Soc. Testing Mats., Part 2, 1920; reprinted as Bulletin 8 of this Laboratory.

Some of the most significant results from wear tests of concrete published in the foregoing reports are repeated in this Bulletin; the reader should, however, refer to the original publication if further details are desired.

The details of tests in Series 98, 129, 134, 135 and 145 will be published in later reports.

In issuing the second printing, no changes have been made in the text, tables or figures.

WEAR TESTS OF CONCRETE

By Duff A. Abrams

Introduction

The wide-spread use of concrete in the construction of roads, pavements and floors is one of the notable features of recent developments in this field.

During the past six years the Structural Materials Research Laboratory, Lewis Institute, Chicago, has carried out eleven different series of tests on the wear of concrete as affected by the following factors:

1. Method of conducting the test;
2. Quantity of mixing water;
3. Quantity of cement;
4. Grading of aggregate;
5. Grading of coarse aggregate;
6. Comparison of different fine aggregates;
7. Comparison of different coarse aggregates;
8. Hydrated lime and other powdered admixtures;
9. Relation of compressive strength to wear;
10. Age of concrete;
11. Time of mixing concrete;
12. Curing condition of concrete.

Wear tests were made in the Talbot-Jones rattler. The history of the development of the present wear tests and a brief bibliography were given in earlier papers.[1] These investigations include tests of about 10,000 wear blocks and probably as many compression tests of concrete cylinders. The wear was measured by the thickness of concrete removed during the test; a low *wear* corresponds to a high *resistance* to wear.

Outline of Tests.

In this paper principal consideration is given to the results of wear tests of concrete; it should be noted, however, that in practically all instances parallel compression tests were made. Concrete was

[1] See "A Method of Making Wear Tests of Concrete," *Proceedings*, Am. Soc. Testing Mats., Vol. 16, Part 2 (1916); also "Effect of Curing Condition on the Wear and Strength of Concrete," *Proc.*, Am. Railway Eng. Assn., Vol. 20 (1919), reprinted as *Bulletin 2* of this Laboratory.

hand-mixed except in Series 89. The general features of each series are given below:

Series 45.—Studies of the method of making wear tests of concrete by means of the Talbot-Jones rattler; about 130 tests. These tests furnished the basis for our paper on "A Method of Making Wear Tests" referred to above.

Series 75.—A study of the effect of curing condition on the strength and wear of concrete; 1:4 mixture of sand with pebbles and crushed limestone as coarse aggregate. Tested at age of 3 months after storing for various periods in damp sand followed by air curing. Three hundred wear blocks. Details of tests were published in *Proceedings,* Am. Ry. Eng. Assn., 1919, and reprinted as *Bulletin 2* of this Laboratory.

Series 89.—An investigation of the effect of time of machine mixing on the wear and strength of concrete; mix 1:4 with concrete of different consistencies and ages. About 200 wear blocks were tested. Details of tests were published in *Proceedings,* Am. Concrete Institute, 1918, p. 43.

Series 98.—A study of the size and grading of aggregate, kind of aggregate and quantity of cement on the wear and strength of concrete. The major portion of the tests was made on a 1:4 mixture using sand and pebbles. Tests were also made on (*a*) concrete from crushed limestone, granite and blast-furnace slag, as coarse aggregate; (*b*) 1:4 mix using pebbles of 21 different gradings; (*c*) 9 different mixtures ranging from 1:6 to neat cement, using a single grading of each of the four aggregates named above; (*d*) wear tests on concrete made of both limestone and pebbles, at ages ranging from 21 days to 6 months. A total of 1780 wear blocks were tested in this series.

Series 114.—This series comprised primarily a study of the effect of hydrated lime on the *strength* of concrete for a wide range of mixtures, consistencies, ages and curing conditions. Wear tests were also made on 1:4 concrete, relative consistency 1.10, and for 10 different gradings of sand and pebble aggregate. Three hundred wear blocks were tested. For details see *Proceedings,* Am. Soc. Test. Mats., Vol. 20, Part 2, p. 173[1] (1920).

Series 129.—An investigation of the effect of variations in the rattler charge on wear of concrete. The total weight and the relative proportions of cast-iron balls of three different diameters were varied over a wide range; 790 wear blocks were tested.

Series 130.—The major portion of this series was a study of the effect of hydrated lime and various other powdered admixtures on

[1] Reprinted as *Bulletin 8* of this Laboratory.

the *strength* of concrete. Wear tests were also made on mixtures ranging from 1 :4½ to 1 :2½, using hydrated lime and five other powdered materials in varying quantities up to 33 per cent of the volume of cement; 500 wear blocks. Details were reported in *Proceedings,* Am. Soc. Test. Mats., Vol. 20, Part 2, p. 176[1] (1920).

Series 133.—Preliminary investigations of the concrete-making properties of several lots of fine and coarse aggregates; 150 wear tests. These were routine tests to bring out the relative merits of different aggregates.

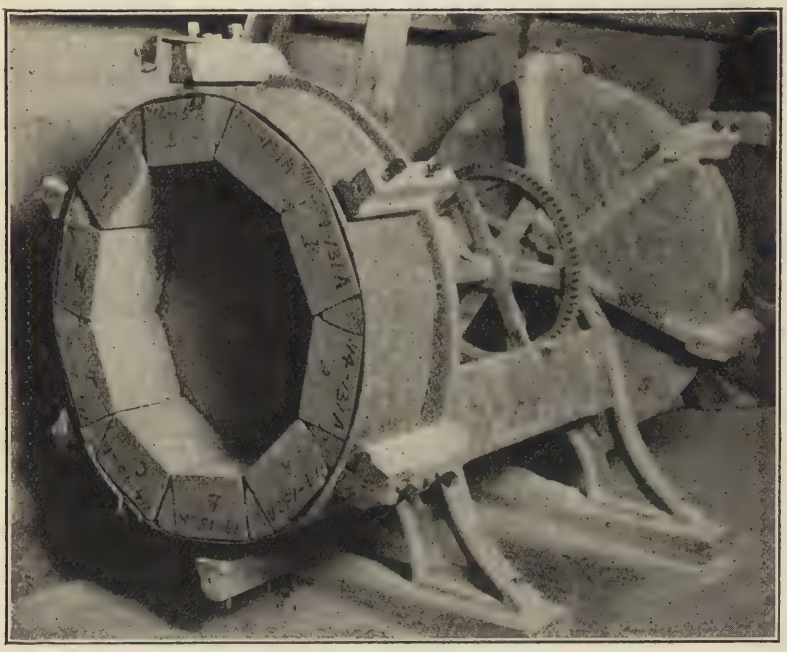


FIG. 1.—Talbot-Jones Rattler.

Concrete wear blocks 8 by 8 by 5 in. in place ready for closing test chamber. Machine has two heads so that duplicate tests can be made in same run.

Series 134.—An investigation of the strength and wearing properties of concrete mixtures suitable for the wearing surface of concrete floors. The influence of size and grading of the aggregate, type of aggregate, cement and water content, and curing conditions were investigated. Tests were made at age of 3 months. About 2800 wear blocks were tested.

Series 135.—An investigation of the concrete-making properties as determined by strength and wear of concrete from about 150

[1] Reprinted as *Bulletin 8* of this Laboratory.

different samples of coarse aggregates collected from widely scattered sources. These materials included 28 samples of pebbles, 35 crushed limestones, 15 crushed granites, 11 traps, 13 sandstones, 24 blast-furnace slags and 45 miscellaneous samples. The coarse aggregates were separated into three sizes and recombined to one of three different gradings. The same sand and cement, and concrete of the same plasticity was used with each coarse aggregate. This series consisted of tests of about 1400 wear blocks and several thousand compression and miscellaneous tests. Details of this series are not given in this report; however, a summary of the principal tests made with coarse aggregates of "Grading A" is given in Table 1.

TABLE 1.—WEAR AND COMPRESSION TESTS OF CONCRETE MADE FROM MISCELLANEOUS COARSE AGGREGATES.

Wear tests of 8 by 8 by 5-in. concrete blocks made in Talbot-Jones rattler.
Compression tests of 6 by 12-in. cylinders.
Mix 1 : 4 by volume of mixed aggregate; approximately same as 1 : 2 : 3 mix.
Relative consistency 1.10; about the same as should be used in the construction of concrete roads to be finished by hand.
Hand-mixed concrete; one specimen to a batch.
Cement: a mixture of five brands of portland cement purchased in Chicago.
Sand from Elgin, Ill., graded 0 to No. 4, used as fine aggregate in all tests.
Each coarse aggregate was screened and recombined to the following grading: No. 4 to ⅜-in., 25 per cent, ⅜ to ¾-in., 50 per cent, ¾ to 1½-in., 25 per cent by volume.
For each aggregate sample, the value for wear was the average of 10 tests and for strength, 5 tests, made on 5 different days.
Specimens stored in damp condition 14 days, then in air until tested at age of 3 months.

Coarse Aggregate					Concrete Tests* (3 months).	
Kind.	Number of Samples Tested.	Unit weight, lb. per cu ft.	Apparent Specific Gravity.	Absorption at 3 hr., per cent by weight.	Compressive Strength, lb. per sq. in.	Depth of Wear, in.
Pebbles	24	102	2.56	1.17	4330	0.51
Crushed Limestone	26	91	2.59	1.14	4560	0.44
Crushed Granite	12	92	2.59	0.32	4350	0.34
Crushed Trap	6	95	2.85	0.12	4210	0.40
Crushed Sandstone	7	86	2.34	3.94	4470	0.45
Crushed Slag	13	88	2.34	2.20	4240	0.48
Crushed Flint	2	83	2.43	....	4850	0.46
Crushed Marble	1	96	2.69	0.39	4620	0.42
Crushed Lava Rock	1	90	2.62	2.50	5350	0.40
Crushed Tufa	1	47	1.27	27.50	1960	0.66
Crushed Fire Brick	1	70	1.92	4.55	5390	0.43
Cement Clinker	2	88	2.22	8.20	5160	0.37
Boiler Cinders	1	40	1.51	8.70	3000	0.85

*Strength tests were also made at ages of 7 and 28 days, and 1 year on many of the aggregates.

Series 145—An investigation of the concrete and mortar-making qualities of about 200 fine aggregates as determined by strength and wear tests of concrete. In collecting these samples special care was taken to secure materials of inferior quality or of unusual characteristics. The same coarse aggregate (pebbles) and the same quantity of cement and the same relative consistency were used throughout. This series consisted of about 1500 wear blocks as well as several thousand compression tests of concrete cylinders, etc. Details of this series are not given in this report.

MATERIALS, TEST PIECES AND METHODS OF TESTING.

The cement used consisted of equal parts of four or five brands of portland cement purchased in Chicago. In general the aggregates were sand and pebbles of limestone origin from the Elgin, Ill., pit of the Chicago Gravel Co. In a number of the tests artificial gradings of these materials were used in studying the effect of size and grading of aggregates. In certain series aggregate from widely scattered sources were used. All concrete was mixed with water from Lake Michigan.

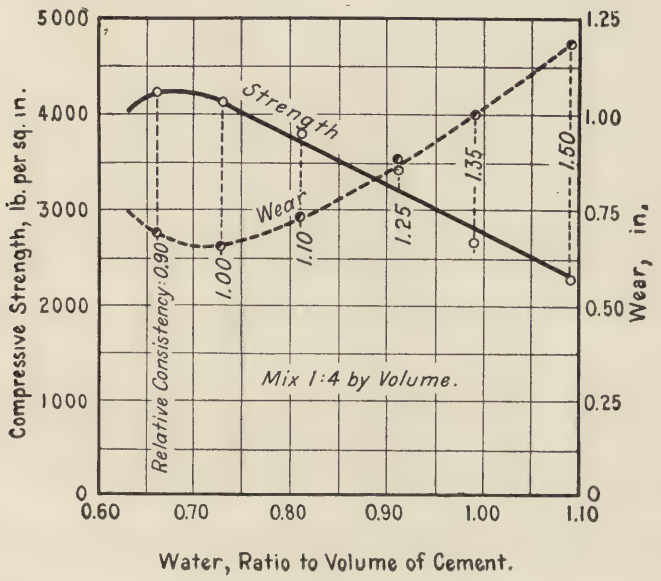


FIG. 2.—Effect of Quantity of Mixing Water on Wear and Strength of Concrete. (Series 75.)

Wear tests of 8 by 8 by 5-in. blocks and compression tests of 6 by 12-in. cylinders.

Hand-mixed concrete.

In general the aggregate was sand and pebbles, graded up to 1½ in. For one curing condition crushed limestone was also used as coarse aggregate.

Tests for 4 curing conditions were averaged. Each value for wear is average of 50 tests, for strength 20 tests.

Age at test, 4 months.

Reproduced from "Effect of Curing Condition on the Wear and Strength of Concrete," by Duff A. Abrams, *Proceedings*, Am. Ry. Eng. Assn., Vol. 20 (1919); reprinted as *Bulletin 2* of this Laboratory.

In this paper concrete mixtures are expressed as one volume of cement to a given number of volumes of aggregate *mixed as used;* 94 lb. of cement was considered to be 1 cu. ft. A 1 : 4 mix with aggregates graded up to 1½ in. was most frequently used; this corresponds closely to 1 : 2 : 3 or 1 : 1½ : 3 mixtures commonly specified for one-course concrete road construction.

The quantity of mixing water is generally expressed in terms of the "relative consistency" of the concrete. A relative consistency of 1.00 requires such a quantity of water that a freshly molded truncated cone 4 in. in diameter at top, 8 in. at bottom and 12 in. high will slump ½ to 1 in. upon removal of the form by a steady upward pull. A relative consistency of 1.10 indicates the use of 10 per cent more water than required for a relative consistency of 1.00. The quantity of mixing water is also expressed by the "water-ratio," or the ratio of volume of water to volume of cement in the batch.

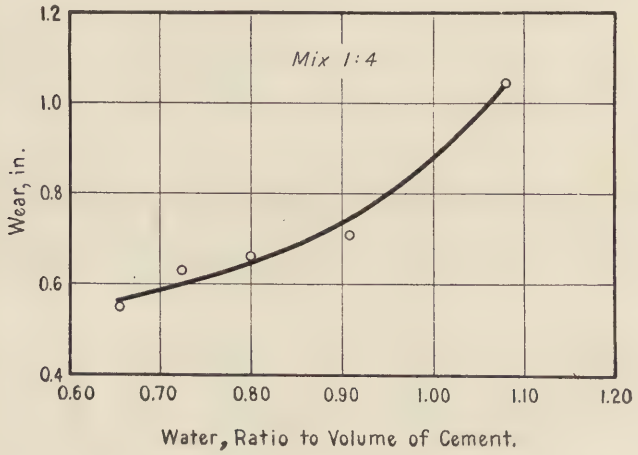


FIG. 3.—Effect of Quantity of Mixing Water on Wear of Concrete. (Series 89.)

Aggregate: sand and pebbles graded up to 1½ in.

Machine-mixed concrete. Each value is average of 30 tests from 6 mixing periods ranging from 15 seconds to 10 minutes.

Specimens stored in damp sand until 2 days prior to testing at age of 2 months.

Reproduced from "Effect of Time of Mixing on the Strength and Wear of Concrete," by Duff A. Abrams, *Proceedings*, Am. Concrete Inst., 1918, p. 38.

The "fineness modulus" is used as a measure of the size and grading of the aggregate. This value is the sum of the percentages in the sieve analysis divided by 100, when the sieve analyses are expressed as percentages coarser than each sieve.[1] A high value of fineness modulus represents a coarse aggregate and a low value a fine aggregate.[2]

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[1] See Standard Method of Test for Sieve Analysis of Aggregates for Concrete (Serial Designation: C 41 — 24) of the American Society for Testing Materials, Standards, 1924, p. 767.

[2] For a discussion of the relation of water-ratio and fineness modulus to the strength of concrete see "Design of Concrete Mixtures," by Duff A. Abrams, *Bulletin 1*, Structural Materials Research Laboratory.

Wear tests were made on concrete blocks 8 in. square and 5 in. thick. In general, each wear block or cylinder was made from a separate batch of concrete mixed by hand in a shallow metal pan; in Series 89 machine-mixed concrete was used. Wear blocks were molded in metal forms which were set on a sheet of building paper placed directly on the concrete floor. The forms were filled with

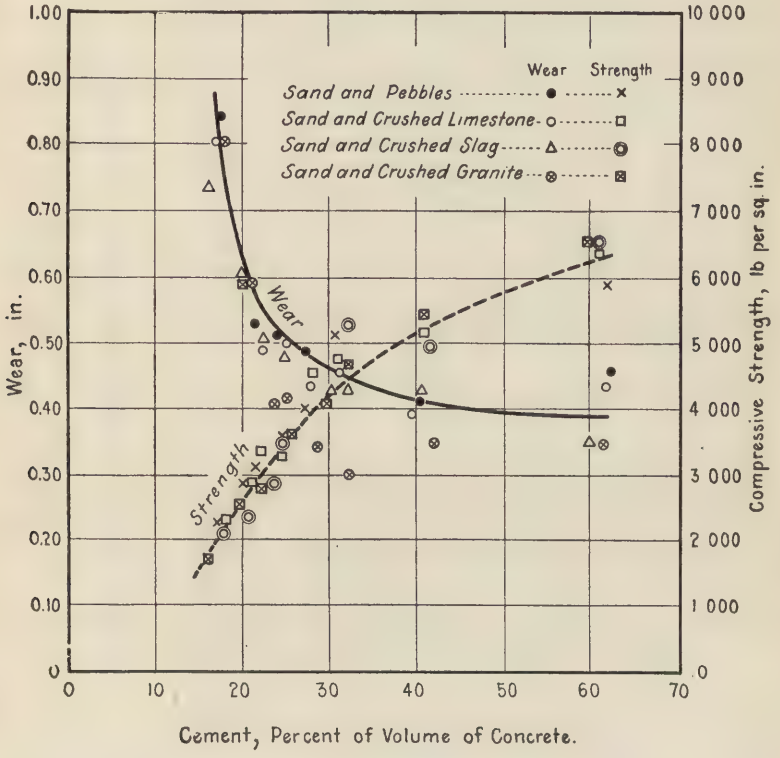


FIG. 4.—Effect of Quantity of Cement on Wear and Strength of Concrete. (Series 98.)

Hand-mixed concrete; relative consistency 1.10.
Each value for wear is average of 10 tests; for strength 2 tests.
Specimens stored in damp sand 14 days; remainder in air.
Age at test, 3 months.

concrete and puddled about 25 times with a ⅝-in. round steel rod pointed at the lower end. More concrete was then placed on the top and leveled off with a trowel. After about 2 hours the tops of the blocks were finished by hand with a wood float. The blocks were allowed to remain in the forms over night; during this period the tops were covered with damp cloths or building paper and damp

sand. Upon removal of the forms the blocks were stored 14 days in damp sand or in a moist room and the remainder in the open air of the laboratory. Tests were generally made at the age of 3 months; variations in the method of storage and age at tests are noted on the diagrams.

In general, the blocks for each condition were tested in sets of 10, 5 each on 2 different days. Our present practice is to make the specimens in sets of 10, 2 each on 5 different days.

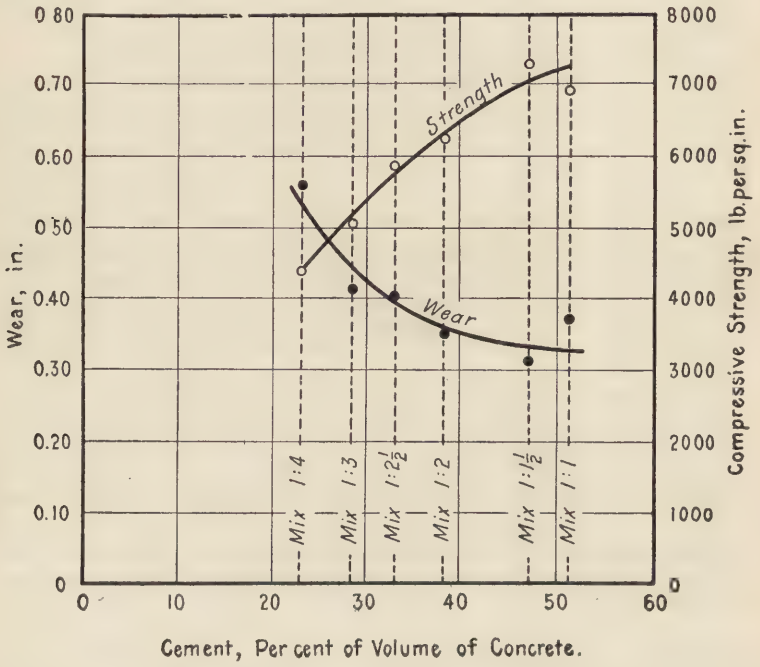


FIG. 5.—Effect of Quantity of Cement on Wear and Strength of Concrete. (Series 134.)

Hand-mixed concrete; relative consistency 1.10.
Aggregate: sand and pebbles from Elgin, Ill.
Each value for wear is the average of 40 tests, and of strength 16 tests. The values for 4 sizes of aggregates ranging from 0 to No. 4 sand to 0 to 1½-in. aggregate were averaged. The specimens for each condition were made on two different days.
Specimens stored in damp sand 14 days, remainder in air. Age at test, 3 months.

Wear tests were made in the Talbot-Jones rattler. This machine consists essentially of a heavy cast-iron head 36 in. in diameter with projective arms for holding the ring of test blocks. The head is rigidly attached to a horizontal shaft and suitable gearing is provided. The test blocks were arranged in a 10-sided polygon inside a heavy

circular band and set in the machine head. The front of the chamber was then closed with a steel plate, and an abrasive charge of cast-iron balls placed in the chamber. The wear was produced by revolving the machine and subjecting the finished surfaces of the blocks to the tumbling action and impact of the balls. Our standard practice is to use 10 3¾-in. balls and about 135 1⅞-in. balls, a total weight of 200 lb. The machine is run for 1800 revolutions at about 30 r.p.m.—

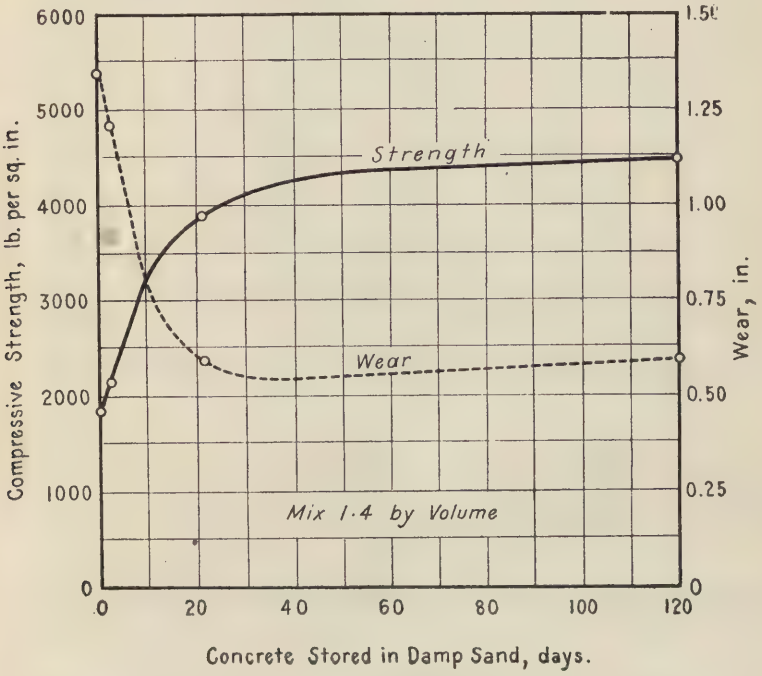


FIG. 6.—Effect of Curing Condition on Wear and Strength of Concrete. (Series 75.)

Note that all tests were made at age of 4 months. The upward trend of the wear curve at the 120-day storage period is due to testing these blocks in a damp condition. Compare Fig. 7. Each value for wear is the average of 60 tests (10 each for 6 consistencies), of strength, 24 tests. Aggregate: sand and pebbles from Elgin, Ill., graded 0 to 1½ in.
Reproduced from "Effect of Curing Condition on the Wear and Strength of Concrete," by Duff A. Abrams, *Proceedings*, Am. Ry. Eng. Assn., Vol. 20 (1919).

900 in one direction and 900 in the other. In two series of tests the total weight and the relative proportions of different sizes of shot in the charge and the number of revolutions were varied. In these tests an intermediate size of shot was also used.

The blocks were weighed before and after test. The loss in weight, calculated to the average thickness of concrete removed by the test, was taken as a measure of the wear.

Fig. 1 shows the Talbot-Jones rattler with the blocks in place ready for the chamber to be closed. This machine is provided with two heads.

Parallel concrete specimens (6 by 12-in. cylinders) were generally made for compression tests at the same time as the wear blocks. The concrete was puddled into the steel forms in 3 equal layers. Three or four hours after molding, the top of each cylinder was capped by means of neat cement paste and a piece of plate glass.

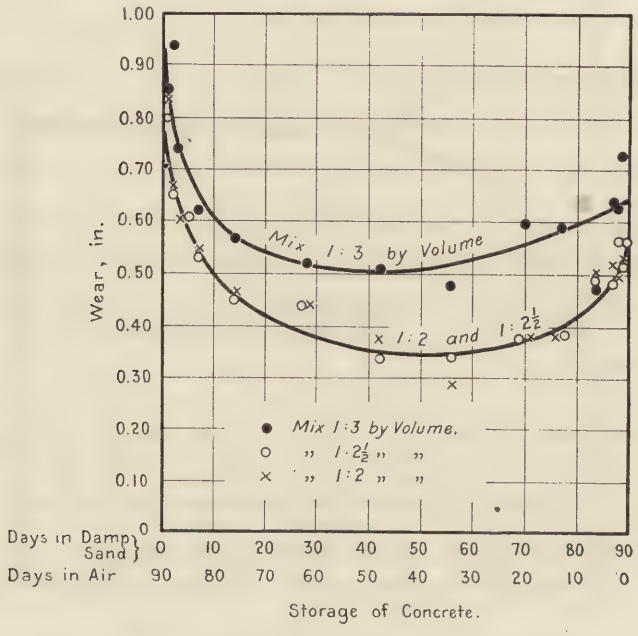


FIG. 7.—Effect of Curing Condition on Wear of Concrete Floor Mixtures. (Series 134.)

Note that all tests were made at age of 3 months. The upward trend of the curve is on account of tests being made with blocks in a damp condition. Compare Fig. 6.
Relative consistency of concrete, 1.10.
Aggregate: sand and pebbles from Elgin, Ill., graded 0 to ⅜ in.
Each value for wear is the average of 10 tests and for strength, 4 tests, made on 2 different days.

TEST DATA.

In these investigations about 10,000 wear tests have been made. Due to the large mass of data, we can present in this paper only typical results from the most significant groups of tests. These values are presented in Table 1 and in diagrammatic form in Fig. 2 to 17. The most important conditions surrounding the tests are indicated in the notes which accompany the table and figures.

DISCUSSION OF TESTS.

The following notes indicate the principal features of the wear tests which have thus far been carried out.

Method of Conducting Tests.—After a study of methods of making wear tests, the Talbot-Jones rattler was adopted. The details of the test method are given above. In standardizing this test an

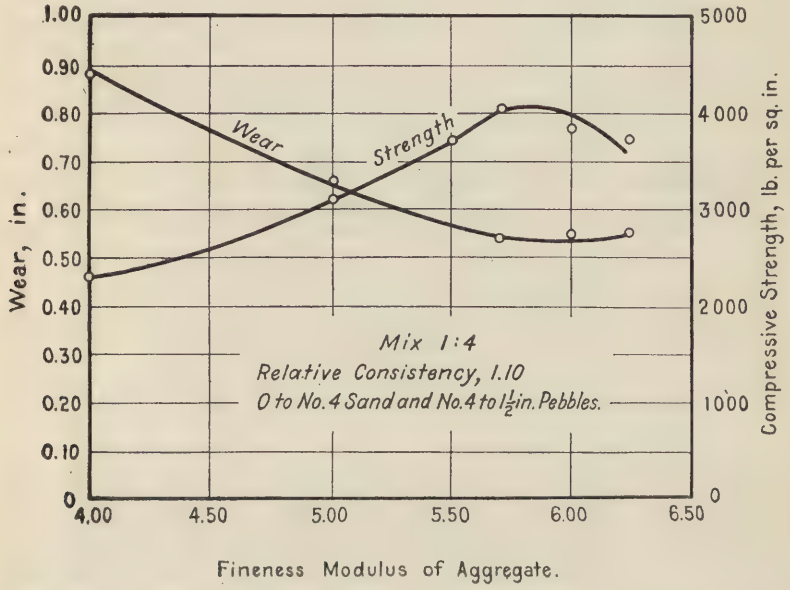
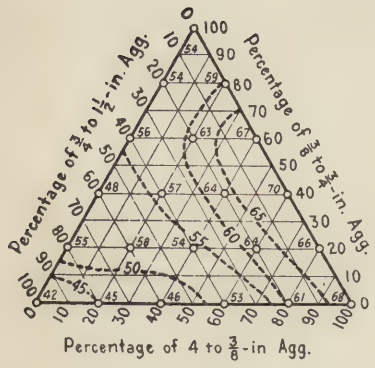


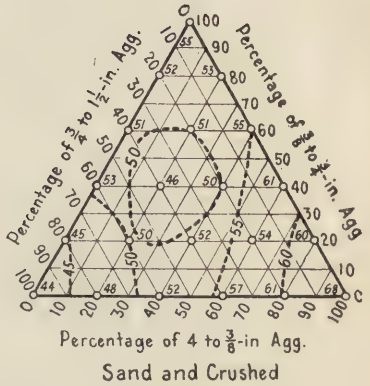
FIG. 8.—Effect of Grading of Aggregates on Wear and Strength of Concrete. (Series 98.)

Aggregate: sand and pebbles from Elgin, Ill., graded 0 to 1½ in.
Each value for wear is the average of 10 tests; for strength, 2 tests, made on 2 different days.
Specimens stored in damp sand; tested damp at age of 3 months.

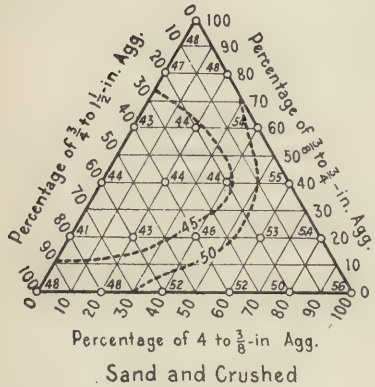
investigation was carried out in which the total weight of cast-iron balls, as well as the relative proportions of balls of three different sizes were varied over a very wide range. Greatest wear was produced by the largest balls. The effect of number of revolutions was also studied; 3000 revolutions gave a wear of about 88 per cent higher than the standard test of 1800 revolutions. The test procedure selected as standard is adapted to a wide range of quality of concrete. A high-grade concrete will show a wear of about ½ in.; a poor concrete may lose as much as 1½ to 2 in. This test gives a combined abrasion and impact action which is not dissimilar to the treatment a concrete surface receives under modern traffic. The advantages of this test as compared with other methods which have been used were pointed out in our paper on "A Method of Making Wear Tests of Concrete."



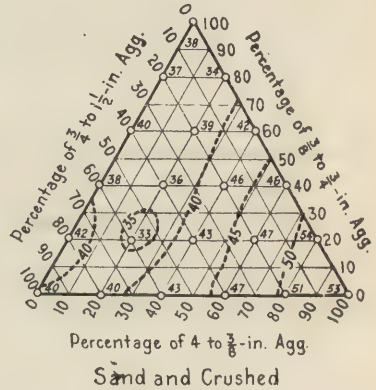
Sand and Pebbles.



Sand and Crushed Limestone.



Sand and Crushed Blast-Furnace Slag.



Sand and Crushed Granite.

VALUES OF WEAR GIVEN IN 0.01-IN.

FIG. 9.—Effect of Grading of Coarse Aggregate on Wear of Concrete. (Series 98.)

Mix 1:4 by volume. Relative consistency of concrete, 1.10.
Each value for wear is the average of 10 tests made on 2 different days.
Specimens stored in damp sand 14 days; remainder in air.
Age at test, 3 months.

Effect of Quantity of Mixing Water.—The effect of quantity of mixing water on the wear of concrete is shown in Fig. 2 and 3. In these diagrams variation in water content is expressed in terms of the water-ratio, or the ratio of the volume of water to the volume of cement in the batch. A water-ratio of 0.80 represents about the consistency which should be aimed at in road construction. Increasing this to 1.00 caused an increase in wear from 0.65 to 0.90 in. In other words, the wear increases rapidly with an increase in the quantity of mixing water. These diagrams confirm the conclusion of many

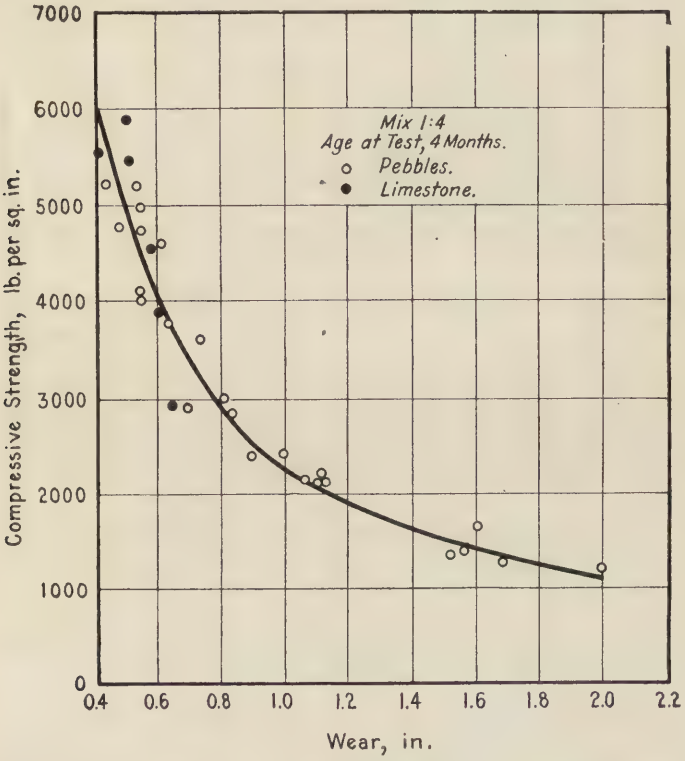


FIG. 10.—Relation Between Wear and Strength of Concrete. (Series 75.)

Aggregate: sand and pebbles, and sand and crushed limestone, graded up to 1½ in.
Each value for wear is the average of 10 tests and for strength, 4 tests made on 2 different days.
Tests for 4 conditions of curing and 6 consistencies are included.
Reproduced from "Effect of Curing Conditions on the Wear and Strength of Concrete," by Duff A. Abrams, *Proceedings*, Am. Ry. Eng. Assn., Vol. 2 (1919); reprinted as *Bulletin* 2.

other investigations carried out in this Laboratory in showing the primary importance of restricting mixing water to the smallest quantity that will produce a plastic, workable concrete. It will be noted from Fig. 2 that the strength curve is almost opposite in form from the wear curve.

Effect of Quantity of Cement is shown in Fig. 4 and 5. In Fig. 4 the mixtures ranged from 1 : 6 to 1 : 1, using pebbles, crushed limestone, granite and slag as coarse aggregates. In Fig. 5 mixtures ranging from 1 : 4 to 1 : 1 were used, with sand and pebbles as aggregate. All tests were made at age of 3 months after curing specimens for 14 days in damp sand and remainder in air. The wear decreased rapidly with the increase in quantity of cement used. It will be

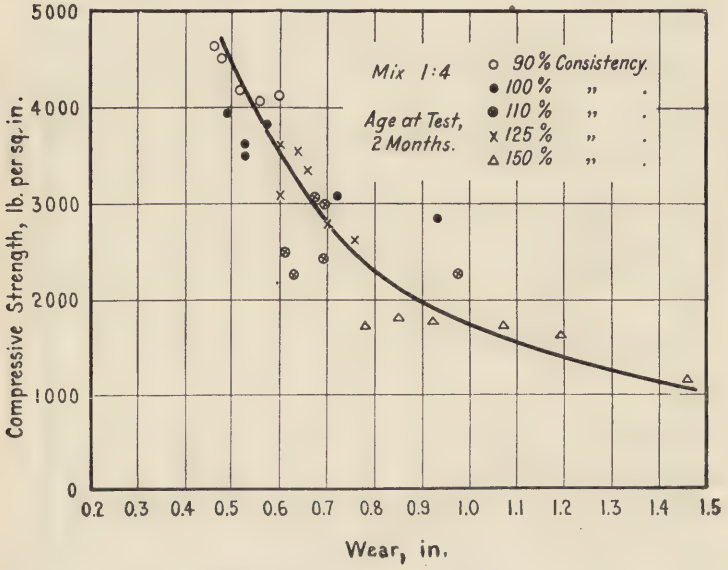


FIG. 11.—Relation Between Wear and Strength of Concrete. (Series 89.)

Machine-mixed concrete; tests from 6 different times of mixing varying from 15 seconds to 10 minutes are included.
Aggregate: sand and pebbles from Elgin, Ill., graded 0 to 1½ in.
Specimens stored in damp sand until 2 days prior to test at age of 2 months.
Each value for wear is average of 5 tests; for strength, 4 tests, from the same batch.
Reproduced from "Effect of Time of Mixing on the Strength and Wear of Concrete," by Duff A. Abrams, *Proceedings*, Am. Concrete Inst., 1918, p. 38. Compare Fig. 3.

noted that here also the strength and wear curves are nearly opposite in form.

Effect of Curing Condition of Concrete is shown in Fig. 6 and 7. Fig. 6 indicates the importance of curing the concrete for a few days in a damp condition before it is subjected to wear. A curing period of 10 days reduced the wear from 1.4 to 0.8 in. Tests were made at the age of 4 months. The wear for all conditions in Fig. 6 is abnormally high, due to the fact that tests from a number of different

consistencies were averaged. All tests in Fig. 7 were made at the age of 3 months, the relative periods of damp sand and air storage being varied. For the 1:3 mixture the wear was reduced from about 0.95 in. to 0.60 in. by curing for 10 days in damp sand. The upward trend of the curves at the right probably resulted from the specimens being tested before they were thoroughly dry, indicating that wet concrete is more affected by wear than similar concrete in a dry condition.

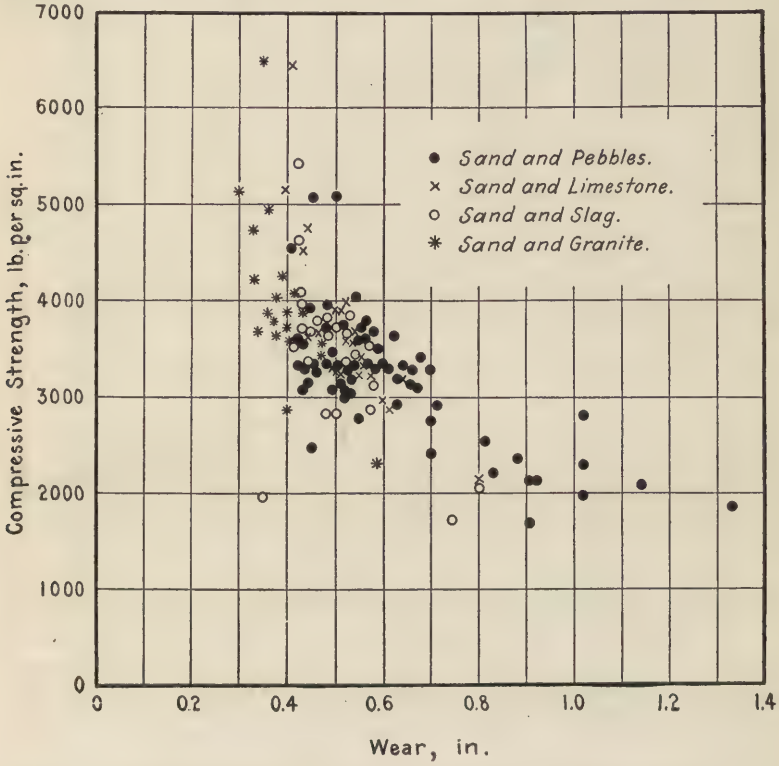


FIG. 12.—Relation Between Wear and Strength of Concrete. (Series 98.)
Hand-mixed concrete; relative consistency, 1.10.
Tests are included for a wide range in size and grading of aggregate and quantity of cement.
Specimens stored 14 days in damp sand; remainder in air. Age at test, 3 months.
Each value for wear is average of 10 tests; strength, 2 tests.

Effect of Grading of Aggregates is shown in Fig. 8. In these tests a 1 : 4 mix of the same consistency was used throughout; the size and grading of the aggregates being varied over a wide range by using different proportions of sand and pebbles. The variation in grading is indicated by the fineness modulus[1] of the aggregate, which is the sum of the percentages coarser than the sieves in the standard

[1] See "Design of Concrete Mixtures," by Duff A. Abrams, *Bulletin 1*, Structural Materials Research Laboratory.

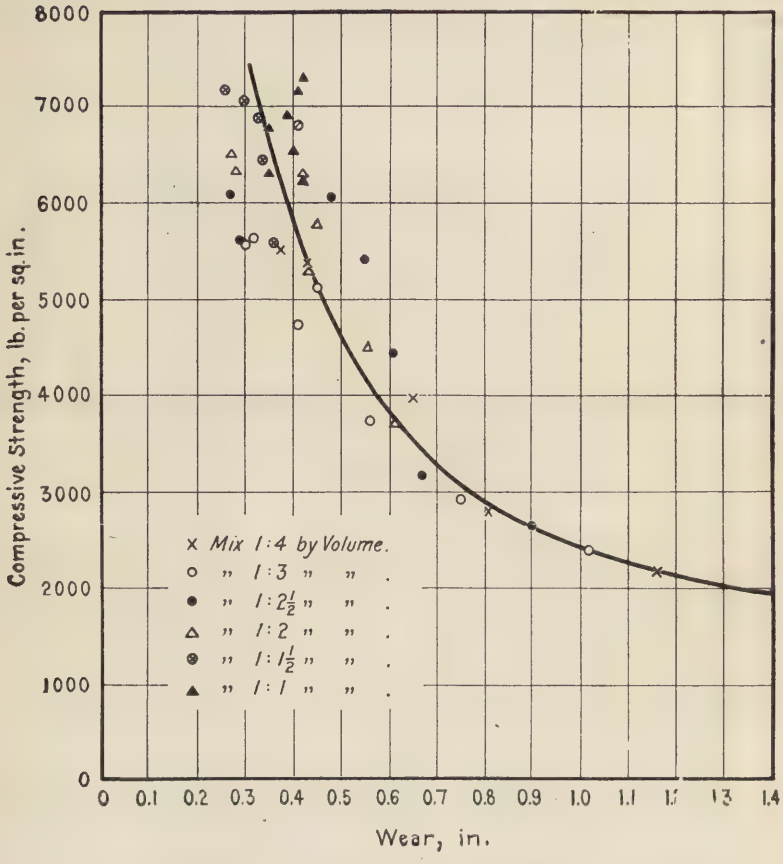


FIG. 13.—Relation Between Wear and Strength of Concrete. (Series 134.)

Hand-mixed concrete; relative consistency, 1.10.
Aggregate: sand and pebbles from Elgin, Ill.
Each value for wear is average of 10 tests; strength, 4 tests.
Tests include aggregates ranging in size from 0 to No. 28 sieve to 0 to 1½ in.
Specimens stored in damp sand 14 days; remainder in air.
Age at test, 3 months.

set. The aggregate of fineness modulus 4.00 was made up of 75 per cent sand and 25 per cent pebbles, that with fineness modulus of 6.00 was made up of 25 per cent sand and 75 per cent pebbles, etc. The wear was materially reduced as the aggregates having a fineness modulus of 5.50 to 6.00 (a well-graded aggregate up to 1½ in.) were reached. All tests presented in Fig. 8 were made on sand and pebbles of limestone origin. In this series, as in Figs. 2, 4, 5 and 6, the wear curve is almost exactly opposite in form from the strength curve.

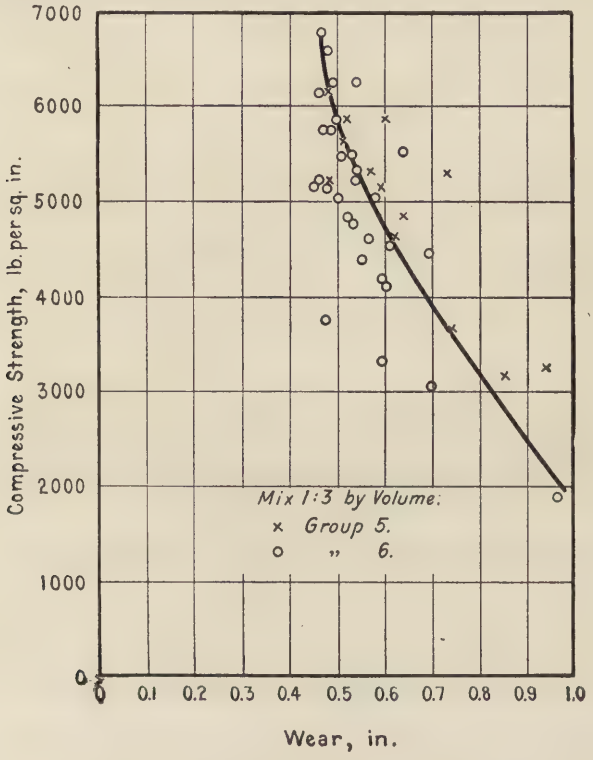


FIG. 14.—Relation Between Wear and Strength of Concrete (Series 134.)

Hand-mixed concrete; relative consistency, 1.10.
Aggregate: sand and pebbles from Elgin, Ill., graded 0 to ⅜ in.
Each value for wear is average of 10 tests; for strength, 4 tests.
Tests are included for 3 mixtures and a wide range of periods of storage in damp sand and air.

Effect of Grading of Coarse Aggregates.—The principal results of the tests with coarse aggregates of different gradings (Series 98) are shown in Fig. 9. Pebbles, crushed limestone, granite and blast-furnace slag were each used in 21 different gradings. A well-graded sand was used throughout as fine aggregate. The gradings of coarse

aggregate are indicated in Fig. 9 by the coordinates of the points on the triangles. Each point represents a definite combination of the three sizes into which the coarse aggregates were screened. The contours of these diagrams show the wear of the concrete in hundredths of inches and indicate that the grading of the coarse aggregate may vary over a wide range without materially affecting the wear. This figure also shows the relation between the wearing qualities of concrete produced by these four types of aggregates. It should be stated that

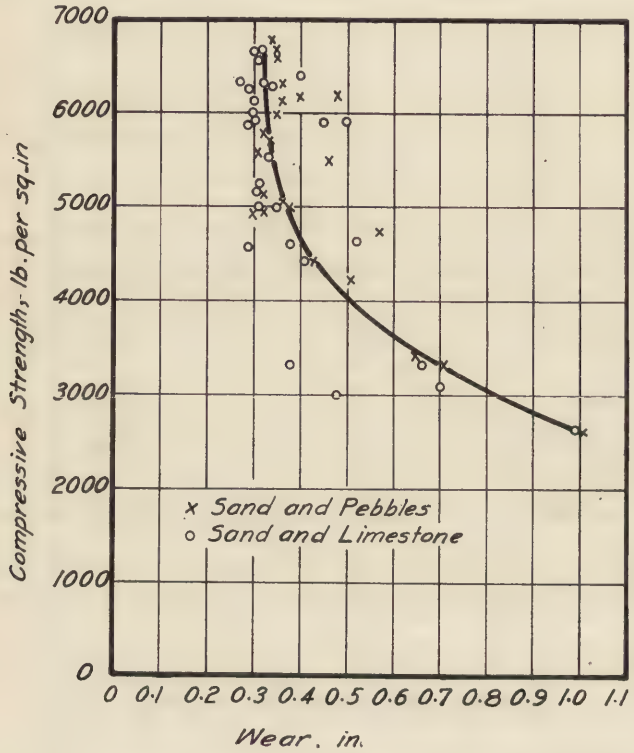


FIG. 15.—Relation Between Wear and Strength of Concrete. (Series 134.)

Hand-mixed concrete: relative consistency, 1.10. Aggregate graded 0 to 1½ in.
Each value for wear is the average of 10 tests and for strength 4 tests made on 2 different days.
Tests are included for a wide range in sand content and for 4 mixtures.
Specimens stored in damp sand 14 days; remainder in air.
Age at test, 3 months.

all of these aggregates were of high grade. The average wear for 21 gradings were as follows: pebbles 0.57 in., crushed limestone 0.53 in., slag 0.46 in., granite 0.42 in. The compressive strength of 6 by 12 in., cylinders made and tested under the same conditions were: pebbles 3360, crushed limestone 3520, slag 3580, and granite

3660 lb. per sq. in. Each of the foregoing values for wear is the average of 210 tests; for strength, 42 tests. All tests were made at the age of 3 months. The relation between wear and strength for these aggregates is shown in Fig. 12. This figure also includes concretes of mixtures ranging from 1 : 6 to 1 : 1. In comparing these concrete strengths with those in Table 1 it should be noted that in the latter tests the aggregates were of *coarser grading* than the average in Fig. 9.

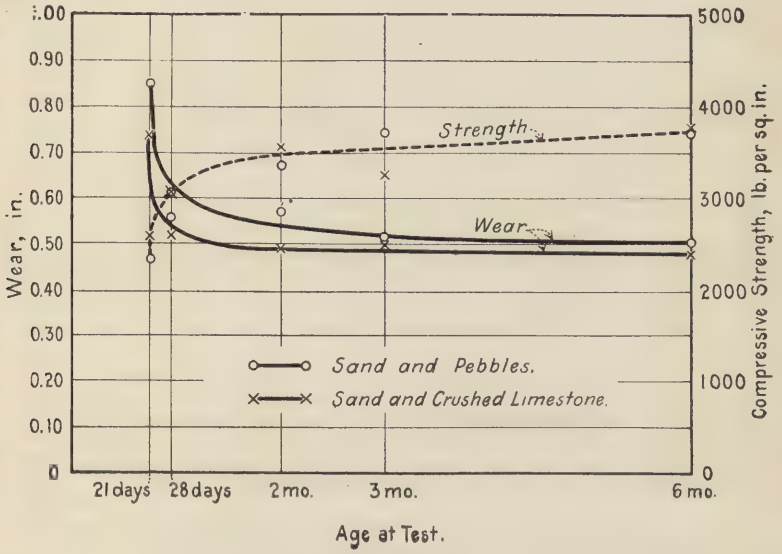


FIG. 16.—Effect of Age on Wear and Strength of Concrete. (Series 98.)

Hand-mixed concrete.
Mix 1 : 4 by volume; relative consistency, 1.10.
Aggregate: sand and pebbles from Elgin, Ill., graded up to 1½ in.
Each value for wear is average of 5 tests and for strength 2 tests, made on same day.
Specimens stored in damp sand 14 days; remainder in air.

Comparison of Different Coarse Aggregates.—Data on the relative merits of pebbles, crushed limestone, granite and slag were referred to in discussing Fig. 4 and 9. A comparison between pebbles of limestone origin and crushed limestone was made also in Series 75 and 134; see Fig. 10 and 15.

In Series 135, tests were made on about 150 samples of coarse aggregates from widely scattered sources. The principal results from tests made on coarse aggregates of "Grading A" are given in Table 1. This grading was as follows: No. 4 to ⅜ in., 25 per cent, ⅜ to ¾ in., 50 per cent, ¾ to 1½ in., 25 per cent by volume. The wide

variety of these samples will be seen when it is stated that the pebbles averaged in Table 1 were from 13, and the crushed limestone from 11 different states. It appears that the wear of concrete is not so much dependent on the qualities of the coarse aggregate used in the wearing surface as is commonly supposed.

It should be emphasized that in these tests all aggregates were of the same grading and care was taken to mix the concrete to as nearly as possible the same consistency. The general neglect of differences in grading of aggregates and consistency of concrete in comparing the concrete-making properties of different types of aggregates have led earlier investigators to the erroneous conclusion that

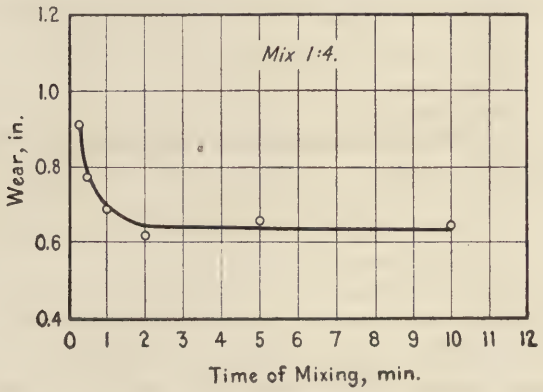


FIG. 17.—Effect of Time of Machine-Mixing on the Wear of Concrete. (Series 89.)

Relative consistency, 1.10.
Aggregate: sand and pebbles from Elgin, Ill., graded up to 1½ in.
Each value for wear is average of 30 tests, 5 each from 6 consistencies.
Specimens stored in damp sand until 2 days prior to test at age of 2 months.
Reproduced from "Effect of Time of Mixing on the Strength and Wear of Concrete," by Duff A. Abrams, *Proceedings*, Am. Concrete Inst., 1918, p. 38.

there was a wider variation in strength of concrete from aggregates of the same type than for aggregates of different types. Our tests show a remarkable uniformity in the concrete strength of aggregates in a given class and much smaller discrepancies between the *different types* of aggregates than is usually supposed. Of the 24 samples of pebbles the lowest concrete strength was 3690 and the highest 4940 lb. per sq. in.—a maximum variation of 33 per cent; the *mean variation* from the average was only 4.8 per cent. The extreme values for wear were 0.74 and 0.44 in. It is notable that the extreme values for strength and wear were found in the same samples. In the case of the 26 crushed limestones the extreme values for strength were 4140

and 5020 lb. per sq. in., or a maximum variation of 21 per cent, and a *mean variation* from the average of 5.3 per cent. The wear for the limestone samples varied from 0.39 to 0.52 in. For the 12 granites, the extreme values for strength were 4130 and 4730 lb. per sq. in., or a maximum variation of 15 per cent, and a *mean variation* from the average of 2.9 per cent. Wear for granite varied from 0.30 to 0.41 in. For the 13 crushed blast-furnace slags the strength varied from 3600 to 4830 lb. per sq. in., or a maximum of 34 per cent, wear varied from 0.39 to 0.64 in., *mean variation* of 6.8 per cent.

These tests show little or no relation between the type of aggregate and the strength of concrete. Low strengths and high wear were given by tufa and cinders; highest concrete strength was found for fire brick, lava and flint; the wear for these samples was about the average. For the usual types of aggregates (pebbles, limestone, granite and trap) the concrete strength was quite uniform. Contrary to general opinion the sandstones gave strengths above the average. The strength of slag concrete compared favorably with the other materials, being about 4 per cent less than the average for pebbles, limestone, granite and trap. Granite showed the lowest wear of any group with a strength about the average of the usual types of aggregates.

Wear Tests with Miscellaneous Fine Aggregate.—A comparison of different fine aggregates was carried out in Series 145. It is not feasible to present the details of these tests; however, it may be stated that the wear of the concrete is, in general, not materially affected by the quality of the fine aggregate so long as it is structurally sound, clean and does not contain an excess of fine material. Further studies are now being carried out in order to bring out the relation between the wear of the concrete and the quality of fine aggregate.

Effect of Hydrated Lime and other Powdered Admixtures.—A complete report on the tests in which hydrated limes and other powdered admixtures were used was presented to the Society last year.[1] No details of these tests are given here. The wear of concrete was not sensibly increased by hydrated lime or other powdered admixtures used up to 20 per cent of the volume of cement.

Relation of Wear to Compressive Strength of Concrete.—In Fig. 2, 8, and 10 to 16, inclusive, the relation between the wear and the compressive strength of concrete is shown. All of these figures show a similar relation between wear and strength. In general, as the

[1] "Effect of Hydrated Lime and Other Powdered Admixtures in Concrete," *Proceedings*, Am. Soc. Test. Mats., Part 2, p. 146 (1920). The foregoing report and a report on a subsequent series of tests on the effect of hydrated lime will be found in *Bulletin 3*, Structural Materials Research Laboratory.

strength increased the wear decreased. As shown in an earlier paper[1] the relation between strength and wear of concrete may be represented by a curve of the form:

$$S = \frac{A}{W^n}$$

where S = the compressive strength of concrete,
W = the wear of concrete as determined by the Talbot-Jones rattler test,
A and n are constants depending on the quality of the concrete and the method of test. The constant A is the compressive strength of concrete which gives a wear of 1 in. by this method.

This relation appears to hold whether variations in strength are due to quantity of cement, size and grading of the aggregate, quantity of mixing water, age of concrete, curing condition of concrete, or other factors which affect the strength. This relation appears to be generally true also for aggregates of different types.

As an illustration of the values of these symbols, the equation for the curve in Fig. 10 is

$$S = \frac{2230}{W^{1.07}}$$

In this group a 1 : 4 mix was used and all tests were made at the age of 4 months.

Effect of Age on the Wear and Strength of Concrete are shown in Fig. 16. The tests in this series were made on blocks which were stored in damp sand 14 days and the remainder in the air of the laboratory. The wear shows a steady decrease with age, the strength a gradual increase, up to 6 months.

Effect of Time of Mixing Concrete.—The effect of time of mixing on the wear of concrete is shown in Fig. 17. The wear for all conditions on this curve is abnormally high due to the fact that a number of wet consistencies were averaged with other tests. The average wear decreased rapidly as the time of mixing increased from 15 seconds to 2 minutes.

[1] "Effect of Curing Condition on the Wear and Strength of Concrete," by Duff A. Abrams, *Proceedings*, Am. Ry. Eng. Assn., Vol. 20, 1919; reprinted as *Bulletin 2* of this Laboratory.

SUMMARY AND CONCLUSIONS[1]

The widespread use of concrete in the construction of roads, pavements and floors is one of the notable features of recent developments in this field. Concrete of a high grade is required for these purposes. The effort to secure concrete of low wear has served to focus the attention of engineers and architects on the factors which enable them to produce concrete of the highest quality.

During the past six years the Structural Materials Research Laboratory, Lewis Institute, Chicago, has carried out a number of researches on the wearing qualities of concrete as affected by:

1. Method of conducting the test,
2. Quantity of mixing water,
3. Quantity of cement,
4. Grading of aggregate,
5. Grading of coarse aggregate,
6. Comparison of different fine aggregates,
7. Comparison of different coarse aggregates,
8. Hydrated lime and other powdered admixtures,
9. Relation of compressive strength to wear,
10. Age of concrete,
11. Time of mixing concrete,
12. Curing condition of concrete.

This report contains brief résumés of these investigations. About 10,000 wear blocks have been tested, as well as several thousand compression cylinders and miscellaneous specimens. The wear as here used is measured by the thickness of concrete removed by the test; a low wear is the same as a *high resistance to wear.* In general, details of the tests are not given; in many instances details have been published elsewhere.

The Talbot-Jones rattler was used with the following procedure: A ring of 10 separately-molded concrete blocks, 8 in. square and 5 in. thick was placed in the machine. The finished surfaces of the blocks were subjected to the tumbling action of a 200-lb. charge of cast-iron balls for 1800 revolutions, requiring about 1 hr. Tests were usually made at the age of 3 months after storing the blocks for 14 days in damp sand or moist air and the remainder in air at ordinary humidity.

[1] This summary was omitted from the original paper in the *Proceedings*, Am. Soc. Testing Mats., 1921.

The following conclusions are based on the wear and compression tests of concrete covered by this report:

(1) The wear on separately molded concrete blocks tested in the Talbot-Jones rattler was much more severe than any encountered in service; however, the test is believed to give trustworthy information on the wearing resistance of concrete of various proportions, consistencies, curing conditions, ages, etc., for use in concrete roads and pavements.

(2) A standardized practice must be followed in making the specimens and conducting the tests if consistent and reliable data are to be secured.

(3) In general the factors which gave concrete of high strength also gave concrete of low wear (a high *resistance to wear*).

(4) Increasing the quantity of cement reduced the wear.

(5) Increasing the quantity of mixing water, beyond the minimum required to produce a plastic concrete, caused a material increase in the wear.

(6) The coarser the grading of the aggregates, up to certain limits, the lower the wear.

(7) Curing concrete under favorable conditions exerted a marked influence in reducing wear.

(8) Wear was materially reduced by longer mixing of the concrete.

(9) Wear was reduced (resistance to wear increased) with the age of the concrete.

(10) The quality of the fine or coarse aggregate produced less effect on wear than is commonly supposed. The wearing resistance of concrete is determined largely by the *quality of concrete* rather than by the type of aggregate. Good concrete can be produced from aggregates which are generally considered inferior, if other factors are properly taken into account.

(11) The wear of concrete was not sensibly increased by the presence of hydrated lime or other powdered admixtures up to 20 per cent of the volume of cement.

Bulletin 11

Structural Materials Research Laboratory
Lewis Institute
Chicago

Flexural Strength of Plain Concrete

By

DUFF A. ABRAMS

Professor in Charge of Laboratory

(Authorized Reprint from the Copyrighted Proceedings of the American Concrete Institute, Vol. XVIII, 1922)

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FOREWORD

This paper was originally published in the Copyrighted *Proceedings* of the American Concrete Institute, Vol. XVIII, 1922. The discussions which appear in the *Proceedings* have been omitted.

Acknowledgment is made to the Institute for permission to reprint this report in bulletin form.

FLEXURAL STRENGTH OF PLAIN CONCRETE

By Duff A. Abrams

INTRODUCTION

The flexural strength of concrete is low as compared with its compressive strength; the use of steel bars to supply this deficiency is the basic principle of reinforced concrete construction. For many years little attention has been given to the flexural strength of concrete, due to the practice of disregarding the tensile stresses in the concrete in the design of *reinforced*-concrete members and structures. With the advent of concrete roads and pavements, the flexural strength of concrete again became important; it may in fact prove the determining factor in working out a rational and economical design of slabs for this purpose. Concrete roads have presented many new engineering problems, one of which is the design of a comparatively thin slab to carry heavy rolling loads. Critical tensile stresses may occur in any direction, in either the top or bottom surface; the span length is uncertain on account of the indeterminate nature of the support.[1] To provide adequate steel reinforcement would involve a prohibitive expense, consequently engineers have come to realize that primary dependence must be placed on the ability of the plain concrete to develop the flexural strength necessary for a proper distribution of the load over the subgrade. The exact thickness of slab necessary for this purpose cannot now be fixed by mathematical analysis, but must be determined as a result of experience. Considerable advance toward a rational design of road slabs may be expected to result from the studies of subgrade soils, the effect of moisture and temperature on the slab and the effect of impact that are now being carried out by the U. S. Bureau of Public Roads and a number of the state highway departments.

Flexural tests of mortar and concrete have been reported by Feret,[2] Fuller and Thompson,[3] Sabin[4] and others, but it seemed desirable to review the subject in the light of recent developments which have led to a better understanding of the factors which enter into the scientific design of concrete mixtures, and a better appreciation of the necessity for exact control of the concrete in carrying out studies of this kind.

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[1]Subgrade Support and Pavement Design, by Clifford Older, Eng. News-Rec., v. 86, p. 210, Feb. 3, 1921.

[2]Etude Experimentale du Ciment Arme, by R. Feret; p. 576, 1906. (See Fig. 13 below.)

[3]Laws of Proportioning Concrete, by Fuller and Thompson; Trans. Am. Soc. Civil Eng., v. 59, p. 67, 1907. (See Fig. 12 below.)

[4]Cement and Concrete, by L. C. Sabin, 1907.

The tensile resistance is the limiting factor in flexural tests of plain concrete, yet a careful distinction must be made between *tension* and *flexural* stresses. Flexural stress here refers to the type of stress developed by beam action. Due to the curvilinear relation between deformation and stress in concrete[5] and other non-homogeneous materials, the tensile stress developed in flexure, when computed by the usual methods, far exceeds the resistance of the material in pure tension. The computed unit tensile strength at which failure occurs is termed the "Modulus of Rupture" of the material. Tests by Mills[6] showed that *tensile strength* of concrete is probably not more than 8 to 10% of its compressive strength in 6-in. cubes, whereas the tests in this report show the modulus of rupture to be 20% or more of the compressive strength. Pure tension tests of concrete are difficult to make and may give misleading results on account of non-uniform distribution of stress across the section.

While it is sound practice to disregard the flexural resistance of the *concrete* in *reinforced* concrete members, it should be noted that load tests on bridges[7] and buildings[8] have shown the concrete to contribute in a marked degree to increasing the load-carrying capacity of the structure.

The tests covered by this report were made as a part of a general investigation of concrete and concrete materials being carried out through the cooperation of Lewis Institute and the Portland Cement Association, at the Structural Materials Research Laboratory, Chicago.

The discussion of these tests is followed by a brief review of the relation of modulus of rupture to compressive strength of a number of other materials of construction.

SCOPE OF TESTS.

750 concrete beams were tested by loads applied at the 1/3 points of a 36-in. span. In general, the beams were of plain concrete 10 in. wide, 7 in. deep. In one group of tests the depth of the beam was varied from 4 to 10 in.; in another group 1 to 8 3/8-in. round reinforcing bars were used. In general the aggregates consisted of sand and pebbles; in one group of tests other types of coarse aggregates were used. Most tests were made at 28 days; in certain groups tests were made at ages of 7 days to 1 year.

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[5]Modulus of Elasticity of Concrete, by Stanton Walker. Proc. Am. Soc. Testing Mat., 1919, Part II.

[6]Materials of Construction, by A. P. Mills, 1915, p. 192. (In stating these percentages certain allowance has been made for discrepancy in ages of specimens tested by Mills.)

[7]Test of a 40-ft. Reinforced Concrete Highway Bridge, by Duff A. Abrams. Proc. Am. Soc. Testing Mat., 1913, p. 884.

[8]Moments and Stresses in Slabs, by Westegaard and Slater, Proc. Am. Concrete Inst., 1921, p. 415, see bibliography, p. 533.

The following topics were studied in this series:—

1. Position of beam during test,
2. Quantity of cement,
3. Quantity of mixing water,
4. Size of aggregate,
5. Grading of aggregate,
6. Curing condition of concrete,
7. Depth of beam,
8. Kind of aggregate,
9. Age of concrete,
10. Relation between flexural and compressive strength,
11. Relation between strength and water-ratio of concrete,
12. Number of steel reinforcing bars,
13. Uniformity of tests.

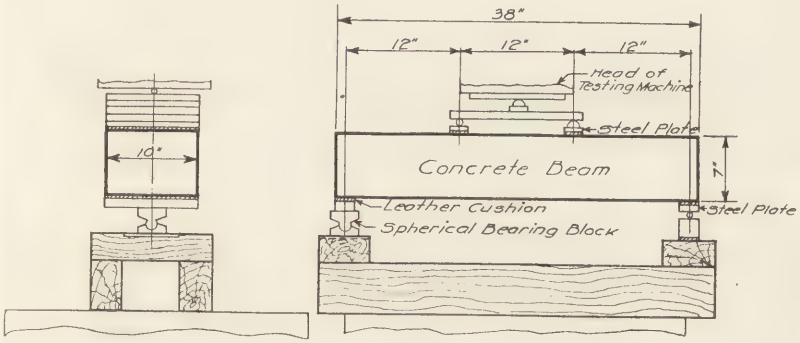


FIG. 1.—METHOD OF LOADING CONCRETE BEAMS.

An important feature of the report is the comparisons between flexural and compressive strength of concrete from the same batches. 750 tests of 6 by 12-in. cylinders are included.

MATERIALS.

The cement consisted of a mixture of equal parts of 4 brands of portland cement purchased in Chicago; complete data of tests are given in Table I.

Sand from Janesville, Wis., and pebbles from Elgin, Ill., were used in most of the tests. In one group crushed stone and slag were used as coarse aggregate. Sieve analyses and miscellaneous data concerning the aggregates will be found in Table II. The sieves used were of square mesh wire cloth recommended by the American Society for Testing Materials.[9]

[9]Tentative Method of Test for Sieve Analysis of Aggregate for Concrete, Proc. A. S. T. M., 1921.

The sieve analysis curves for aggregates (Fig. 2) are platted in terms of the percentages coarser than each of the sieves in the set, using as abscissae the logarithms of the clear openings in inches. Since the clear opening of each sieve is just double the width of the next smaller sieve, the logarithmic scale consists simply of a series of equi-distant ordinates. Special paper is not required for a logarithmic scale for this purpose. The fineness modulus[10] of the aggregate is a useful measure of its size and grading; it is the sum of the percentages in the sieve analysis expressed as above, divided by 100. Graphically it is proportional to the area

TABLE I.—TESTS OF PORTLAND CEMENT.

The cement used in all tests consisted of a mixture of equal parts of four brands purchased in Chicago.

Tests were made in accordance with Standard Specifications and Tests for Portland Cement of American Society for Testing Materials.

MISCELLANEOUS TESTS.

Cement Lot No.	Fineness, Residue on No. 200 Sieve.	Normal Consistency, per cent by weight.	Time of Setting.				Soundness Test (over boiling water).
			Vicat Needle.		Gillmore Needle.		
			Initial.	Final.	Initial.	Final.	
			h. m.	h. m.	h. m.	h. m.	
5219	18.8	24.0	3 40	8 20	5 45	9 40	OK
5259	17.6	23.0	3 45	8 00	6 30	8 30	OK

MORTAR STRENGTH TESTS.

1 : 3 Standard Sand Mortar.

Values for strength are given in pounds per square inch.

Cement Lot No.	Mixing Water per cent.	Tensile Strength of Briquets.					Compressive Strength of 2 by 4-in. Cylinders.				
		7 d.	28 d.	3 m.	6 m.	1 y.	7 d.	28 d.	3 m.	6 m.	1 y.
5219	10.5	235	365	425	380	405	1670	2570	3520	4250	3840
5259	10.3	280	430	410	385	355	1720	2870	3710	4150	4370

under the sieve analysis curves in Fig. 2. A well-graded concrete sand has a fineness modulus of 2.25 to 3.25; a coarse aggregate graded No. 4 to 1½ in. has a value of about 7.00.

TEST PIECES.

In general flexural tests were made on plain concrete beams 10 in. wide, 7 in. deep and 38 in. long. In one group of tests the depth was varied from 4 to 10 in. In another group one to eight ⅜-in. round bars were used as reinforcement. Parallel compression tests were made on 6 by 12-in. cylinders from the same batches.

[10]For further details see "Design of Concrete Mixtures,"* by Duff A. Abrams, Bull. 1, Structural Materials Research Laboratory, Lewis Institute, Chicago.

The quantities of aggregate required for each batch were determined by weight on the basis of the unit weight of the aggregates mixed as used. The quantity of water for a batch was measured by means of a calibrated tank. All mixtures were by volume; that is, one volume of cement to a

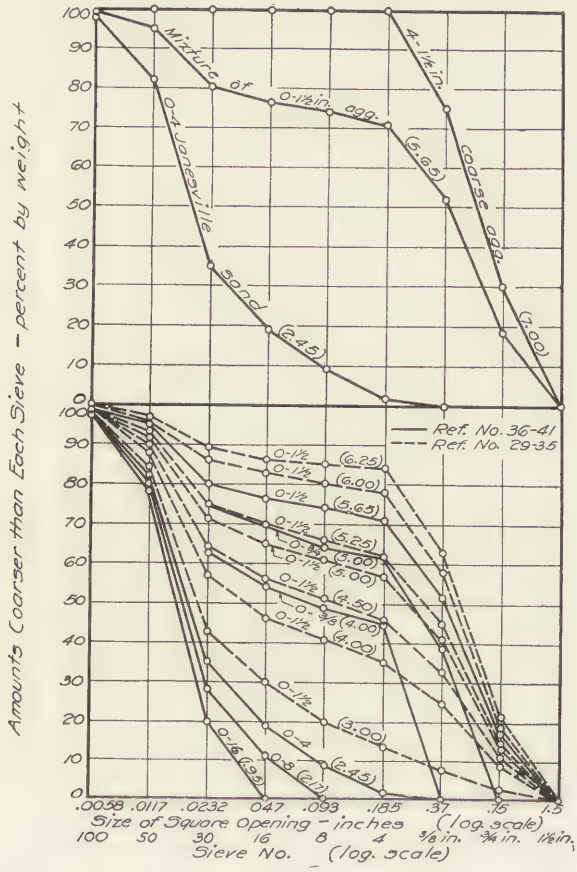


FIG. 2.—SIEVE ANALYSIS CURVES OF AGGREGATES USED IN TESTS.

Details are given in Table II.

given number of volumes of aggregate were mixed together. The mixtures are expressed as 1: 6, 1: 4, etc. regardless of the size or grading of the aggregate. One sack of cement (94 lb.) was considered 1 cu. ft. The consistency or workability of the concrete was measured by the "flow

table"[11]. Concrete with relative consistency 1.00 gave a flow of about 180; other relative consistencies were based on proportional quantities of mixing water. A relative consistency of 1.10 gave a flow of about 220.

The concrete was mixed in a Smith "Mascot" mixer of 3½ cu. ft. capacity. Sufficient concrete was mixed to make 2 beams and 2 cylinders. Each batch was mixed 1 minute after all materials were in the machine.

TABLE II.—SIEVE ANALYSIS AND UNIT WEIGHT OF AGGREGATES.

Square mesh wire cloth sieves manufactured by The W. S. Tyler Co., Cleveland, O., were used in making sieve analyses. Each sieve has a clear opening twice the width of the preceding.

Sieve analysis curves are platted in Fig. 2.

Ref. No.	Aggregate. Kind.	Size.	Sieve Analysis. Amount Retained on Each Sieve, per cent by Weight. 100	50	30	16	8	4	⅜	¾	1½	Fineness Modulus of Aggregate.*	Unit Weight, lb. per cu. ft.
36	Janesville sand	0–No. 16	97	78	20	0	..	..	..	..	..	1.95	108
37	Janesville sand	0–No. 8	98	80	28	11	0	..	..	..	..	2.17	111
38	Janesville sand	0–No. 4	98	82	35	19	9	2	0	..	..	2.45	113
39		0–⅜ in.	99	90	63	54	49	45	0	..	..	4.00	123
40		0–¾ in.	99	93	75	69	64	61	39	0	..	5.00	128
1–28, 41		0–1½in.	99	95	80	76	74	71	52	18	0	5.65	130
29	Janesville sand and Elgin pebbles	0–1½in.	98	84	43	30	20	14	8	3	0	3.00	118
30	Janesville sand and Elgin pebbles	0–1½in.	99	88	57	46	41	35	25	9	0	4.00	127
31		0–1½in.	99	90	64	56	51	46	33	11	0	4.50	131
32		0–1½in.	99	92	71	65	61	57	41	14	0	5.00	132
33		0–1½in.	99	93	75	70	66	62	45	15	0	5.25	133
34		0–1½in.	100	96	86	83	80	78	58	19	0	6.00	127
35		0–1½in.	100	97	89	86	85	84	63	21	0	6.25	124
42–53 59–64	Janesville sand and Elgin pebbles	0–1½in.	99	95	80	76	74	71	52	18	0	5.65	130
54	Janesville sand and crushed slag	0–1½in.	99	95	80	76	74	71	52	18	0	5.65	118
55	Janesville sand and crushed limestone	0–1½in.	99	95	80	76	74	71	52	18	0	5.65	129
56	Janesville sand and crushed granite	0–1½in.	99	95	80	76	74	71	52	18	0	5.65	121
57	Washed Elgin sand and Elgin pebbles	0–1½in.	99	95	86	80	72	67	49	17	0	5.65	127
58	Unwashed Elgin sand and Elgin pebbles	0–1½in.	100	98	91	86	81	73	50	18	0	5.97	130

* Sum of per cents in sieve analysis, divided by 100.

Twin beams were tested in different positions, at different ages, or after storage under different conditions, etc.

The wood forms for the concrete beams were set on a sheet of building paper to prevent bonding with the concrete floor. The forms were thoroughly painted before using and were kept oiled in order to prevent absorption of water. The concrete was placed in two layers, each layer

[11]Time of Set of Concrete, by Watson Davis; Proc. Am. Soc. Testing Mat., 1921, p. 995.

being puddled with a ⅝-in. steel bar pointed at the lower end. After the forms were filled, the concrete was leveled off with a trowel and finished with a wood float. The beams remained in the form over night, being covered with damp burlap sacks. After removal of the forms the beams were stacked compactly on end and kept covered with damp burlap sacks until 28 days old. Beams for test at 3 months and 1 year were placed in the moist room at the age of 28 days. In one group of tests the specimens were stored in a damp condition for different periods, followed by periods of dry air storage.

The concrete cylinders were molded from the same batch from which beams were made. Metal forms made of cold-drawn steel tubing were used.

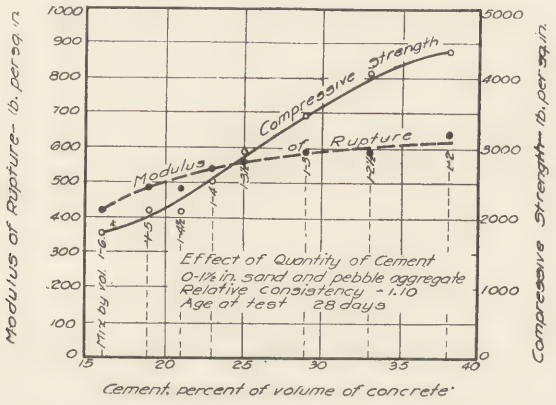


FIG. 3.—EFFECT OF QUANTITY OF CEMENT ON FLEXURAL AND COMPRESSIVE STRENGTH OF CONCRETE.

Data from Table III.

Plain concrete beams 10 in. wide, 7 in. deep, loaded at ⅓ points of 36-in. span: compression tests of 6 by 12-in. cylinders.

Each point is based on 20 tests made on 10 different days.

Beams stored under damp burlap; cylinders in moist room.

Each form stood on a machined cast-iron base plate. The concrete was puddled in the forms in 3 layers, using a ⅝-in. round bar pointed at the lower end. The forms remained in place over night. After the removal of the forms the specimens were stored in a moist room with the humidity near the saturation point and a temperature of about 65 to 70°F. In making the concrete specimens we followed the methods of the American Society for Testing Materials.[12]

The five or more specimens included in averaging the results for a given set of tests were made on different days. One complete round of

[12]Tentative Methods for Making Compression Tests of Concrete; Proc. A. S. T. M., 1921, p. 579.

specimens was made before beginning the second round. This served to distribute accidental variations of materials, manipulation or test conditions. Any value in the series can be compared directly with any other.

METHODS OF TESTING.

Both beam and cylinder tests were made in a 200,000-lb. Olsen universal testing machine. The beams were loaded at the one-third points of a 36-in. span. They were supported and loaded in such a manner as to prevent restraint. One end rested on a roller and the other on a spherical bearing block. The load was transmitted to the beam through leather cushions which prevented concentration of the load due to minor irregularities in the surfaces. The method of loading is shown in Fig. 1.

Both beams and cylinders were tested in a damp condition immediately after removal from storage, except in the case of the group in which combined moist and dry storage was used.

TEST DATA.

Complete data of the tests are given in Tables III to VIII and in Fig. 3 to 11. Only averages are reported; in most instances the values are the average of 5 tests made on different days.

DISCUSSION OF TESTS.

The flexural strength of concrete beams is measured by the modulus of rupture. The modulus of rupture may be defined as the tensile stress developed by beam action, assuming that the stress and deformation are directly proprotional to the distance from the neutral axis of the beam. The modulus of rupture of a rectangular beam freely supported at the ends and loaded at the one-third points of the span is determined by the following relation:

$$R = \frac{WL}{bd^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

Where R = Modulus of rupture of the material,
W = Total load applied at one-third points,
L = Span length,
b = Breadth of beam,
d = Depth of beam.

In case of most of the beams used in this investigation (width 10 in., depth 7 in., span 36 in., load applied at one-third points) the modulus of rupture is given by the relation:

$$R = 0.073W \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

Where R is expressed in pounds per square inch and W in pounds.

In the reinforced-concrete beams (Table VIII) the modulus of rupture was calculated in the same way, that is, the presence of steel was disregarded.

It will be noted that tests on both beams and cylinders of 1: 4 mix, aggregate graded 0 to 1½ in., relative consistency 1.10, stored in the moist room and tested in damp condition at age of 28 days appear in practically all tables and figures. This was considered a *typical* mix for concrete roads. These conditions gave a modulus of rupture of 550 lb. per sq. in. and a compressive strength of 2580 lb. per sq. in. These values are based on 25 beam tests and 115 cylinder tests, made throughout the series. It is interesting to note how this group of tests falls into each of the classifications into which the data have been divided.

With few exceptions the beams failed by nearly vertical cracks between the load points.

Effect of Position of Beam During Test. In general the beams were loaded as molded; that is, with the bottom of the beam in tension. It seemed important to determine whether the position of the beam exerted any influence on its flexural strength. In one group of tests the beams were tested with the bottom in tension and with bottom in compression. Results of these tests are given in Table III. In the first group the mixture varied from 1: 6 to 1: 2; in the second group the mixture was 1: 4 by volume, but the consistency varied from relative consistency 0.90 to 1.50. Aggregates in all cases consisted of a mixture of sand and pebbles graded up to 1½ in. Both groups of tests show that there is little or no difference in the flexural strength of the beam due to the position of the load; the only exception to this statement is found in the wetter mixtures which gave a higher modulus of rupture with the *top* in tension.

Effect of Quantity of Cement. The tests in Table III also give information on the effect of quantity of cement on the flexural strength of concrete. The mixture varied from 1: 6 to 1: 2. Each point on the modulus of rupture curve in Fig. 3 is based on the average of tests of 20 beams (10 with top as molded in tension and 10 with bottom in tension). Increasing the quantity of cement increased both the flexural and the compressive strength of the concrete; however, the modulus of rupture was less affected by the quantity of cement than the compressive strength. The modulus of rupture was relatively lower for the rich mixtures than for the lean, as compared with the compressive strength of 6 by 12-in. cylinders from the same concrete. The modulus of rupture for the richer mixes (1: 2 and 1: 2½) was about 14% of the compressive strength; for the leaner mixtures (1: 6 and 1: 5) about 23% of the compressive strength; for a 1: 4 mix (about the same as the 1: 1½: 3 or 1: 2: 3 mixes usually specified for concrete roads) the modulus of rupture was about 21% of the compressive strength of 6 by 12-in. cylinders. For the usual range of mixtures (1: 4 to 1: 5) the ratio was about 23%.

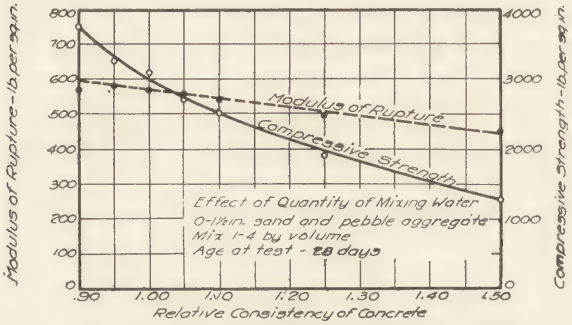


FIG. 4.—EFFECT OF QUANTITY OF MIXING WATER.

Data from Table III.

Each point is based on 20 tests of each kind, made on 10 different days.

TABLE III.—EFFECT OF QUANTITY OF CEMENT AND MIXING WATER.

Aggregate: sand from Janesville, Wis., and pebbles from Elgin, Ill.; graded up to 1½ in. Fineness modulus, 5.65.

Age at test, 28 days.

Specimens tested damp.

Each value for modulus of rupture is the average of 10 tests, and for compressive strength 20 tests, made on 10 different days.

Ref. No.	Mix by Volume.	Cement, per cent of Volume of Concrete.	Relative Consistency.	Water-Ratio of Concrete.	Modulus of Rupture of Beams, lb. per sq. in.			Compressive Strength of 6 by 12-in. Cylinders, lb. per sq. in.	Modulus of Rupture, per cent of Compression.
					Bottom*	Top.*	Aver.		
EFFECT OF QUANTITY OF CEMENT. (See Fig. 3.)									
1, 2.....	1 : 6	16.4	1.10	1.03	430	420	425	1820	23.4
3, 4.....	1 : 5	19.0	1.10	0.92	500	490	495	2140	23.1
5, 6.....	1 : 4½	20.7	1.10	0.87	480	510	495	2130	23.2
7, 8.....	1 : 4	23.0	1.10	0.82	560	540	550†	2580†	21.3
9, 10.....	1 : 3½	25.4	1.10	0.76	590	540	565	2980	19.0
11, 12....	1 : 3	28.7	1.10	0.71	600	590	595	3480	17.1
13, 14....	1 : 2½	33.0	1.10	0.64	590	590	590	4110	14.3
15, 16...	1 : 2	38.7	1.10	0.59	660	620	640	4390	14.6
				Average	550	540	545	2950	19.5
EFFECT OF QUANTITY OF MIXING WATER. (See Fig. 4.)									
17, 18....	1 : 4	23.8	0.90	0.68	590	560	575	3760	15.3
19, 20....	1 : 4	23.5	0.95	0.72	580	600	590	3280	18.0
21, 22....	1 : 4	23.4	1.00	0.75	580	560	570	3100	18.4
23, 24....	1 : 4	23.2	1.05	0.78	570	550	560	2720	20.6
7, 8.....	1 : 4	23.0	1.10	0.82	560	540	550†	2580†	21.3
25, 26....	1 : 4	22.5	1.25	0.92	460	540	500	1920	26.0
27, 28....	1 : 4	22.3	1.50	1.08	400	500	450	1300	34.6
				Average	535	550	540	2660	22.0

* Part of concrete beam (as molded) which was exposed to tensile stress during loading.

† Average of 25 beam tests and 115 cylinder tests; the same values are used in Tables IV to VIII.

Effect of Quantity of Mixing Water is shown in Table III and Fig. 4. Tests were made on 1: 4 mix at age of 28 days. The quantity of mixing water is expressed in terms of relative consistency and the water-ratio of the concrete. Consistency 1.00 is such as to give a flow of 180. A relative consistency of 0.90 is about as dry a mix as can be considered plastic with this method of molding specimens; a consistency of 1.50 is quite wet and shows considerable free water on top of the concrete. Both the modulus of rupture and compressive strength were reduced by increasing

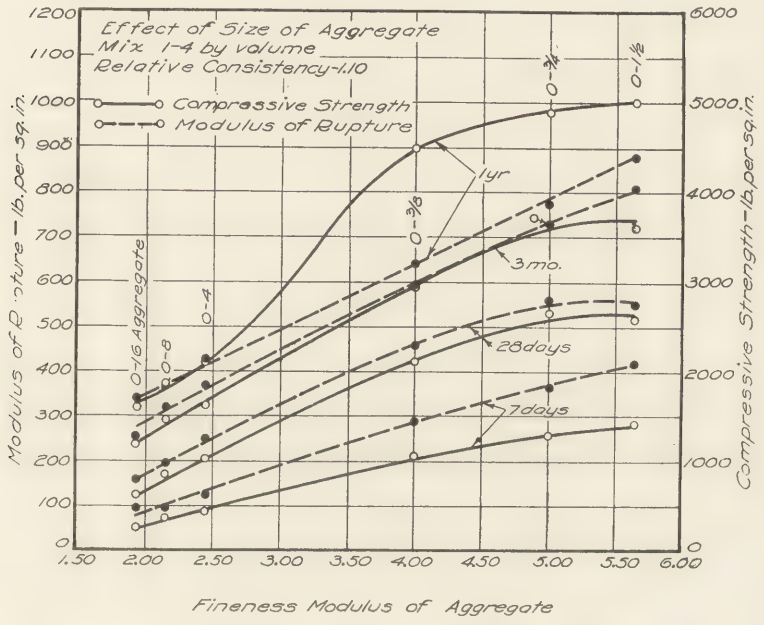


FIG. 5.—EFFECT OF SIZE OF AGGREGATE.

Data from Table IV.
Janesville sand and Elgin pebbles; see Table II for sieve analysis.
Each point is based on 5 tests of each kind made on different days.

the quantity of mixing water. However, the modulus of rupture was less affected than the compressive strength. For the drier mixtures the modulus of rupture was 15% of the compressive strength; for the wetter mixtures about 35%. While the flexural strength of the wetter mixtures is *relatively* higher than for the drier ones, it should be noted that the modulus of rupture of consistency 1.50 is 450, while the values for consistencies 0.95 to 1.10 averaged about 570 lb. per sq. in.—an increase of 26%. The latter consistencies represent those which should be aimed at

in concrete road construction. These tests confirm other tests made in this Laboratory and elsewhere in showing the importance of restricting the quantity of mixing water used in concrete.

Effect of Size of Aggregate is shown in Table IV and Fig. 5. Tests were made on 1: 4 mixtures, using aggregates varying in size from 16-mesh

TABLE IV.—EFFECT OF SIZE AND GRADING OF AGGREGATE.

Aggregates: sand from Janesville, Wis., and pebbles from Elgin, Ill. Aggregates of *different size* were obtained by separating sand and pebbles into various sizes and recombining as shown by sieve analyses in Table II and Fig. 1. *Different gradings* of aggregates were produced by mixing sand (0 to No. 4) and pebbles (No. 4 to 1½ in.) in different proportions.

Mix, 1 : 4 by volume. Relative consistency, 1.10.

Specimens tested damp.

Each value is the average of 5 tests made on different days.

Ref. No.	Aggregate. Size.	Aggregate. Fineness Modulus.	Water-Ratio of Concrete.	Modulus of Rupture of Beams, lb. per sq. in. 7 d.	28 d.	3 m.	1 y.	Compressive Strength 6 by 12-in. Cylinder, lb. per sq. in. 7 d.	28 d.	3 m.	1 y.	Modulus of Rupture, per cent of Compression. 7 d.	28 d.	3 m.	1 y.
				EFFECT OF SIZE OF AGGREGATE. (See Fig. 5.)											
36	0–16	1.95	1.29	95	160	255	340	270	620	1190	1600	35.2	25.8	21.5	21.2
37	0–8	2.17	1.25	95	195	320	370	360	850	1470	1860	26.4	23.0	21.8	19.9
38	0–4	2.45	1.20	125	250	370	425	430	1010	1620	2100	29.4	24.8	22.8	20.2
39	0–⅜	4.00	0.98	290	455	595	640	1040	2110	2930	4490	27.9	21.6	20.3	14.3
40	0–¾	5.00	0.87	365	560	730	775	1290	2650	3650	4890	28.3	21.2	20.0	15.9
41	0–1½	5.65	0.82	420	550*	810	880	1410	2580	3590	5000	29.8	21.3	22.6	17.6
			Aver.	230	360	510	570	800	1640	2410	3320	29.5	22.9	21.5	18.2
				EFFECT OF GRADING OF AGGREGATE. (See Fig. 6.)											
29	0–1½	3.00	1.11	165	255	410	450	620	1290	1640	2330	26.6	19.8	25.0	19.3
30	0–1½	4.00	0.98	230	390	505	570	950	2000	2550	3230	24.2	19.5	19.8	17.7
31	0–1½	4.50	0.93	285	485	610	645	1090	2190	2750	3830	26.2	22.2	22.2	16.9
32	0–1½	5.00	0.87	325	505	660	710	1160	2410	3580	4510	28.0	21.0	18.4	15.8
33	0–1½	5.25	0.85	365	555	735	820	1320	2940	3810	5340	27.7	18.9	19.3	15.4
41	0–1½	5.65	0.82	420	550*	810	880	1410	2580*	3590	5000	29.8	21.3	22.6	17.6
34	0–1½	6.00	0.78	405	600	735	825	1300	2250	3310	4400	31.2	26.7	22.2	18.8
35	0–1½	6.25	0.77	385	590	730	865	1140	1990	2840	4080	33.8	29.6	25.7	21.2
			Aver.	320	490	650	720	1120	2210	3010	4090	28.4	22.4	21.9	17.8

* Average of 25 beam tests and 115 cylinder tests; same values used in Tables III, V, VI, VII and VIII

sand to a concrete aggregate graded up to 1½ in. The "effective grading" of the aggregate is measured by the fineness modulus. Tests were made at ages of 7 days, 28 days, 3 months and 1 year. With the same quantity of cement, the modulus of rupture and the compressive strength of the concrete increased rapidly as the size of aggregate was increased, up to a point where the aggregate became too coarse for the quantity of cement. The rate of increase of strength of concrete was nearly pro-

portional to the change in fineness modulus of the aggregate. The modulus of rupture at 28 days varied from 160 to 560 lb. per sq. in.; and the compressive strength from 620 to 2650 lb. per sq. in. Except for the 16-mesh sand the ratio between the modulus of rupture and the compressive strength was nearly constant for a given age—21 to 23% at 28 days. In other words the transverse and the compressive strengths are

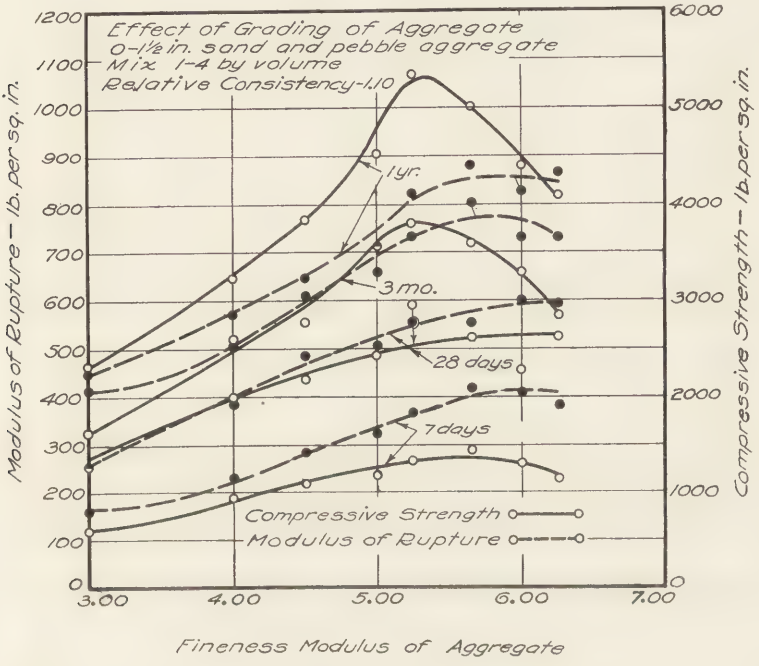


FIG. 6.—EFFECT OF GRADING OF AGGREGATE.

Data from Table IV.

Aggregate gradings were obtained by mixing Janesville sand (0 to No. 4) and Elgin pebbles (No. 4 to 1½-in.) in different proportions; sieve analysis given in Table II.

Each point is based on 5 tests of each kind made on different days.

affected in a similar manner by differences in the size of aggregate, as shown by the practically parallel curves for a given age in Fig. 5.

Effect of Grading of Aggregate is shown in Table IV and Fig. 6. Tests were made on a 1: 4 mix at ages of 7 days, 28 days, 3 months and 1 year. The aggregates of different grading used in these tests were produced by mixing different proportions of sand (0 to No. 4) and pebbles (No. 4 to

1½ in.). The finest grading consisted of 86% sand and 14% pebbles; the coarsest grading consisted of 14% sand and 86% pebbles, as shown by the sieve analyses in Table I. With the same quantity of cement, the modulus of rupture and the compressive strength increased rapidly as the grading of the aggregate was made coarser (by increasing the relative proportion of pebbles) until a grading was reached which was too coarse for the quantity of cement. The flexural and compressive strength were affected in essentially the same way by changes in grading of the aggregate. The rate of increase of strength of the concrete was nearly proportional to the increase in fineness modulus of the aggregate. If the values in Fig. 5 and 6 are platted on the same diagram it will be found that they are practically coincident, although the relation between the strength and fineness modulus of the aggregate is based on aggregate gradings made up in entirely different ways.

Effect of Curing Condition of Concrete; mix 1:4 tested at the age of 28 days. The results are given in Table V and Fig. 7. The curing conditions ranged from 28 days under damp burlap (moist room for cylinders) to 28 days in air of the Laboratory. The flexural strength and the compressive strength were affected in the same way, as shown by the similarity of the curves in Fig. 7. The modulus of rupture of beams cured in dry air for the entire period of 28 days was 370 lb. per sq. in.; cured under damp burlap for 28 days was 550 lb. per sq. in.; an increase of 48%. Curing 7 days under damp burlap and 21 days in dry air gave 470 lb. per sq. in.; an increase of 27% over the dry air storage for 28 days. It will be recalled that the specimens which were cured under the most unfavorable conditions were prevented from drying out for the first 24 hr.; had they been allowed to dry out from the beginning the modulus of rupture and compressive strength would have been still lower. These tests show the great advantage of damp curing on both the flexural and compressive strengths and confirm the results of earlier tests[13] made in this Laboratory and elsewhere.[14]

Effect of Depth of Beam; 1:4 mix, tested at 28 days. The depth of beam varied in this group from 4 to 10 in. Data are given in Table VI and Fig. 8. The curves show that the modulus of rupture was only slightly affected by the depth of the beam within the range of these tests. There is an indication of somewhat lower values for the deeper beams. The 4-in. beams gave a modulus of rupture of 545 lb. per sq. in.; the 8 and 10-in. beams averaged 525 lb. per sq. in. Flexural tests of other materials have shown that wide variations in ratio of depth of beam to span produce important variations in modulus of rupture; in general, the deeper beams give the higher values.

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[13]Effect of Curing Condition on the Wear and Strength of Concrete, by Duff A. Abrams; Bull. 2, Struc. Mat. Research Lab.

[14]Relation between Methods of Curing Standard Concrete Test Specimens and Their Compressive Strength at 28 days, by H. W. Green; Proc. Am. Soc. Testing Mat., 1919, Part II, p. 607.

Effect of Kind of Aggregate. Tests were made on 1 : 4 mix at age of 7 days, 28 days, 3 months and 1 year, using the following aggregates:

(1) Janesville, Wis., sand
  (a) Elgin pebbles (limestone origin)
  (b) Crushed blast furnace slag
  (c) Crushed limestone
  (d) Crushed granite (Wisconsin)

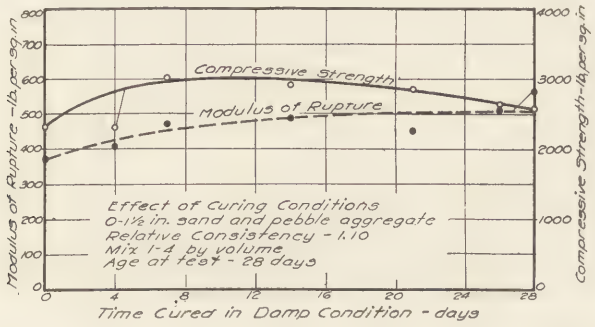


FIG. 7.—EFFECT OF CURING CONDITION OF CONCRETE.

Data from Table V.

Each point is based on 5 tests of each kind made on different days.

Beams cured under damp burlap, cylinders in moist room, for periods shown by abscissae.

TABLE V.—EFFECT OF CURING CONDITION OF CONCRETE.

Mix, 1 : 4 by volume. Relative consistency of concrete, 1.10; water-ratio, 0.82.
Age at test, 28 days.
Aggregate: sand from Janesville, Wis., and pebbles from Elgin, Ill.; graded up to 1½ in.
Each value is the average of 5 tests made on different days.
Data platted in Fig. 7.

Ref. No.	Storage.		Modulus of Rupture of Beams, lb. per sq. in.	Compressive Strength of 6 by 12-in. Cylinders, lb. per sq. in.	Modulus of Rupture, per cent of Compression.
	Damp Burlap.	Dry Air.			
7, 8	28 d.	0 [zero]	550*	2580*	21.3
42	26 d.	2 d.	510	2630	19.4
43	21 d.	7 d.	450	2850	15.8
44	14 d.	14 d.	485	2920	16.6
45	7 d.	21 d.	470	3020	15.6
46	4 d.	24 d.	410	2330	17.6
47	0 d.	28 d.	370	2340	15.8
			Average 465	2670	17.5

* Average of 25 beam tests and 115 cylinder tests; same values used in Tables III, IV, VI, VII, and VIII.

7 and 28-day tests only were made on the following aggregates:

(2) Elgin, Ill., sand (limestone origin) washed
  (a) Elgin pebbles.
(3) Elgin sand—unwashed
  (a) Elgin pebbles.

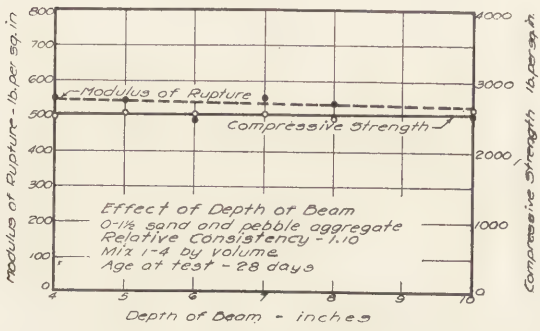


FIG. 8.—EFFECT OF DEPTH OF BEAM ON THE FLEXURAL STRENGTH OF CONCRETE.

Data from Table VI.

Plain concrete beams 4 to 10 in. deep, 10 in. wide, loaded at ⅓ points of a 36-in. span.

Each point is based on 5 tests of each kind made on different days.

TABLE VI.—EFFECT OF DEPTH OF BEAM ON THE FLEXURAL STRENGTH OF CONCRETE.

Mix, 1 : 4 by volume. Relative consistency of concrete, 1.10; water-ratio, 0.82.
Aggregate: sand from Janesville, Wis., and pebbles from Elgin, Ill.; graded up to 1½ in.
Age at test, 28 days.
Specimens tested damp.
Each value is the average of 5 tests made on different days.
Data platted in Fig. 8.

Ref. No.	Depth of Beam, inches.	Modulus of Rupture of Beams, lb. per sq. in.	Compressive Strength of 6 x 12-in. Cylinders, lb. per sq. in.	Modulus of Rupture, per cent of Compression.
48	4	545		21.2
50	5	540		20.9
52	6	490	2580*	19.0
53	7	550*		21.3
51	8	535		20.8
49	10	510		19.8
		Average 530		20.6

* Average of 25 beam tests and 115 cylinder tests; same values used in Tables III, IV, V, VII and VIII.

The coarse aggregate (and consequently the total aggregate in each batch) were similarly graded. The sieve analyses are given in Table II and Fig. 2. There was no great discrepancy between the flexural and compressive strengths given by the pebbles, slag and limestone; the granite

gave somewhat lower values both in flexure and compression. The reason for this probably lies in the low absorption of the granite. The absorption of water by the other aggregate resulted in a lowering of the water-ratio of the batch, although the concrete was mixed to the same consistency or workability at the beginning. The washed Elgin sand (silt 0.5%) gave values for modulus of rupture a little lower than unwashed (silt 2.0%),

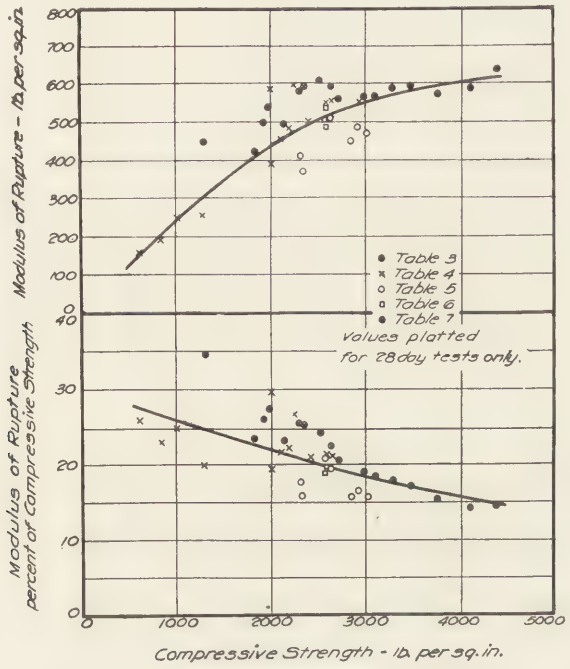


FIG. 9.—RELATION BETWEEN STRENGTH AND WATER-RATIO OF CONCRETE.

Data from Tables III to VII.

Plain concrete beams 10 in. wide, 7 in. deep, loaded at ⅓ points of a 36-in. span; compression tests of 6 by 12-in. cylinders.

but the compressive strength was slightly higher, indicating that there is little difference in strength of concrete due to slight differences in silt content. The objection to the use of sands of high silt content is not that the strength of concrete of *proper* consistency is materially reduced, but that with wet mixes frequently used in concrete road construction the silt is floated to the surface where it produces a weak and friable concrete.

Effect of Age of Concrete. In Tables IV and VII, both flexural and compression tests are reported on 1: 4 mixes at ages of 7 days, 28 days,

TABLE VII.—EFFECT OF KIND OF AGGREGATE.

Mix, 1 : 4 by volume.
Relative consistency, 1.10; water-ratio, 0.82.
Aggregate: sand, 0 to No. 4; and coarse aggregate, No. 4 to 1½ in.; all of same grading.
Specimens tested damp.
Age at test, 28 days.
Each value is the average of 5 tests made on different days.

Ref. No.	Kind of Aggregate.		Modulus of Rupture of Beams, lb. per sq. in.				Compressive Strength of 6 by 12-in Cylinders, lb. per sq. in.				Modulus of Rupture, per cent of Compression.			
	Sand.	Coarse.	7 d.	28 d.	3 m.	1 y.	7 d.	28 d.	3 m.	1 y.	7 d.	28 d.	3 m.	1 y.
7,8	Janesville.....	Elgin pebbles	420	550*	810	880	1410	2580*	3590	5000	29.8	21.3	22.6	17.6
54	Janesville.....	Slag.....	450	585	765	760	1240	2300	3150	4530	36.3	25.4	24.3	16.8
55	Janesville.....	Limestone..	440	595	790	830	1320	2350	3280	3970	33.4	25.3	24.1	20.9
56	Janesville.....	Granite.....	375	540	665	725	1010	1980	2960	3760	37.1	27.3	22.4	19.3
57	Elgin washed..	Elgin pebbles	405	595	...	...	1490	2640	....	....	27.2	22.5	....	....
58	Elgin unwashed	Elgin pebbles	425	610	...	...	1340	2520	....	....	31.7	24.2	....	....
		Average	420	580	760	800	1300	2390	3240	4320	32.6	24.3	23.4	18.8

* Averge of 25 beam tests and 115 cylinder tests; same values used in Tables III, IV, V, VI and VIII.

TABLE VIII.—EFFECT OF NUMBER OF STEEL REINFORCING BARS.

Beams: Depth, 7 in.; width, 10 in.; span, 36 in.
Longitudinal reinforcing bars were spaced equally across the width and 1 in. from the bottom of the beam The total depth of beams varied from 6.9 to 7.1 in.
Mix, 1 : 4 by volume. Aggregate: sand and pebbles graded 0 to 1½ in.
Relative consistency of concrete, 1.10; water-ratio, 0.82.
Age at test, 28 days.
Specimens tested damp.
Each value is the average of 5 tests made on different days.
Compressive strength of 6 by 12-in. concrete cylinders (average of 115 tests) was 2580 lb. per sq. in.

Ref. No.	Number of ⅝-in. Round Steel Bars.	Percentage of Steel.	Total Load on Beam, pounds.	Computed Stresses, lb. per sq. in.					Type of Beam Failure.
				Tension in Steel.	Compression in Top Fibre.	Bond.	Shearing Unit Stress.	Modulus of Rupture.	
7, 8	0	None	7,870†	.....	....	...	70	550†	Tension
59	1	0.18	7,850	73,000*	1470*	570	70	560*	Tension
60	2	0.36	10,390	49,400*	1460*	380	90	730*	Tension
61	3	0.54	15,010	49,100*	1850*	380	140	1085*	Tension
62	4	0.72	19,640	48,900*	2190*	380	180	1435*	Diagonal shear
63	6	1.09	25,800	43,800*	2500*	340	240	1885*	Diagonal shear
64	8	1.46	28,060	36,800*	2530*	290	270	1990*	Diagonal shear

* Tension in concrete not considered in computing steel stress or top fibre stress. Steel not considered as taking stress in computing modulus of rupture.

† Average of 25 beam tests; same values used in Tables III to VII.

3 months and 1 year. The values from these tests are platted in Fig. 11. These tests show that both the flexural and compressive strength are proportional to the logarithm of the age of the concrete. The flexural strength increased less rapidly than compression, as shown by the average

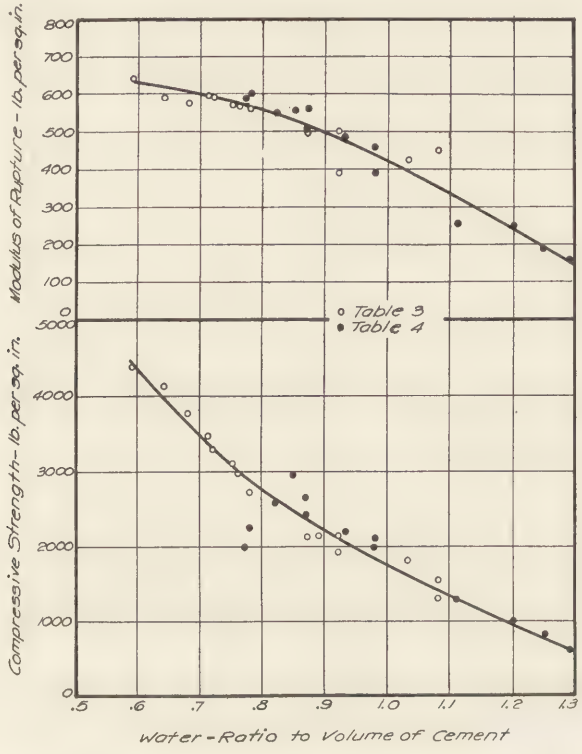


FIG. 10.—RELATION BETWEEN THE TRANSVERSE AND COMPRESSIVE STRENGTH OF CONCRETE.

Data from Tables III and IV.

Plain concrete beams 10 in. wide, 7 in. deep, loaded at ⅓ points of a 36-in. span; compression tests of 6 by 12-in. cylinders.

ratio of flexure to compressive strength of 30% at 7 days, 23% at 28 days, 22% at 3 months and 18% at 1 year. Other studies of the effect of age on the compressive strength of concrete[15] have shown that this logarithmic relation holds indefinitely so long as the concrete does not dry out.

[15]Effect of Age on the Strength of Concrete, by Duff A. Abrams, Proc. Am. Soc. Testing Mat., 1918, Part II; see also Concrete, July, 1921, p. 14.

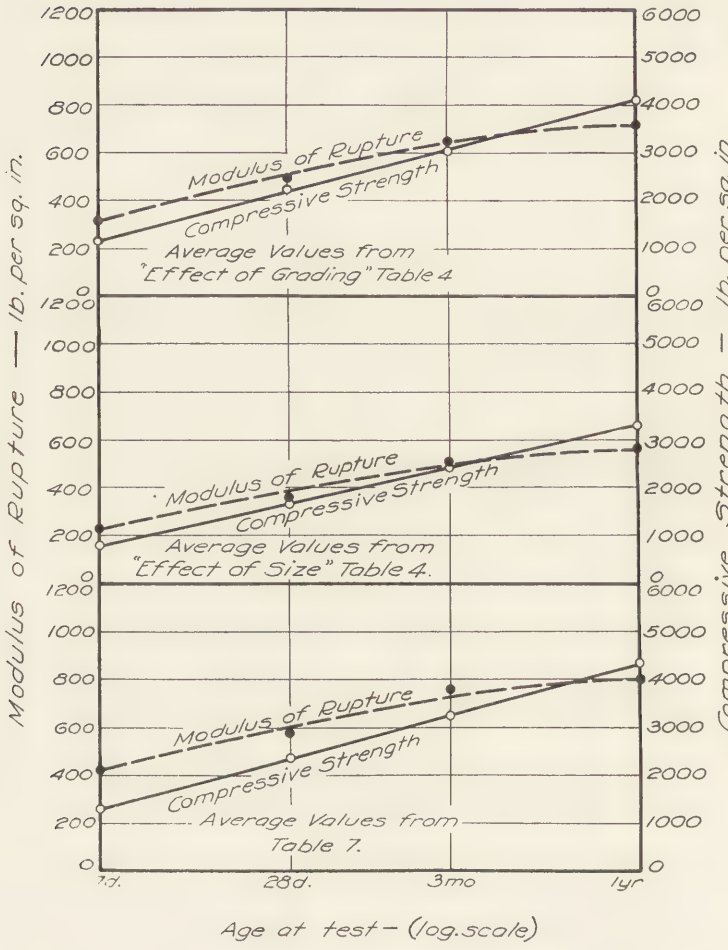


FIG. 11.—EFFECT OF AGE ON THE TRANSVERSE STRENGTH OF CONCRETE.

Data from Tables IV and VII.

Each point is the average of several different gradings, or kinds of aggregate.

Beams cured under damp burlap; cylinders in moist room.

Relation between Modulus of Rupture and Compressive Strength. Many of the tables show the modulus of rupture in terms of the compressive strength of the concrete. The values for 28-day tests from Tables III to VII inclusive are platted in Fig. 10. The upper diagram gives the actual values and shows a fairly consistent relation between the modulus of rupture and the compressive strength regardless of the mixture, con-



FIG. 12.—RELATION BETWEEN TRANSVERSE AND COMPRESSIVE STRENGTH OF CONCRETE. (BY FULLER AND THOMPSON.)

From "Laws of Proportioning Concrete." Trans. Am. Soc. Civil Eng., v. 59, p. 67 (1907).

sistency, size and grading of aggregate, etc. This relation may be expressed by the equation:

$$R = 0.29S - 0.000032S^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

where R = modulus of rupture of plain concrete beams
S = compressive strength of 6 by 12-in. concrete cylinder.

This is the equation of the upper curve in Fig. 5 when stresses are given in pounds per square inch. The modulus of rupture is relatively higher for the weak concrete; at 28 days it is about 26% of the compressive strength for 1000-lb. per sq. in. concrete; 22% for 2000-lb.; 19% for 3000-lb. and 15% for 4000-lb. concrete.

Relation between Strength and Water-Ratio of Concrete. The water-ratio is defined as the ratio of volume of water to volume of cement in the batch. A water-ratio of 0.75 to 1.00 covers the usual range of mixtures. In platting Fig. 9 only 28-day tests from Tables III and IV were used. It will be noted that the water-ratio was varied, due to the following causes:

(1) Quantity of cement,
(2) Consistency of concrete,
(3) Size of aggregate,
(4) Grading of aggregate.

In spite of the wide differences in the *cause* of variation of water-ratio, it is found that the relation between strength and water-ratio can be expressed by a single curve for each form of test. The lower curve shows the usual relation which has been found between the compressive strength and water-ratio.[16] The upper curve shows the relation between water-ratio and modulus of rupture of concrete to be of an entirely different form from that found for compression. The compressive strength drops off rapidly at first, then less rapidly with an increase in the quantity of mixing water. The modulus of rupture drops off slowly at first, then more rapidly. The comparison between these relations may be best seen by a specific example. Fig. 9 shows that by increasing the water-ratio from 0.80 to 1.20 (an increase of 50% in mixing water) the compressive strength is reduced from 2750 to about 950 lb. per sq. in.; and the modulus of rupture from 550 to 240 lb. per sq. in. In other words, the wetter concrete gives a compressive strength of about ⅓ and a modulus of rupture of about ½ that produced by the concrete in which care was taken to restrict the mixing water to a reasonable quantity.

Effect of Number of Steel Reinforcing Bars. In one group of tests, beams of standard size were reinforced with 1 to 8 ⅜-in. round steel bars, placed with centers 6 in. below the top of the beam. Table VIII gives total loads, the computed tensile stress in the steel, compressive stress in the top fiber of beams, the bond stress between the concrete and steel, shearing unit stress and modulus of rupture. In calculating the tension in the steel, the stresses carried by the concrete was not considered; in computing the modulus of rupture the stress carried by the steel was not considered. The tests show that no effect is produced by one reinforcing bar. Upon failure of the concrete the stress is transmitted to the reinforcing bar. The stress carried by one bar when stressed to the ultimate simply counterbalances the failure of the concrete in tension. With 4 to 8 bars, failure was produced by diagonal tension which did not develop the tensile strength of the steel.

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[16]Design of Concrete Mixtures, by Duff A. Abrams; Bull. 1, Structural Materials Research Lab., 1918.

Uniformity of Tests. The tables and diagrams show unusual uniformity in the tests in this series. In only a few instances are the points off the smooth curves which represent the relations between strength and other factors. The strength of concrete depends on so many factors; it is inevitable that some discrepancies should appear. The making of five or more test pieces on different days seems to eliminate most accidental variations. The methods followed in making these tests are recommended to others who may be engaged in concrete testing.

EARLIER FLEXURAL TESTS OF CONCRETE.

Fig. 12 gives the results of flexural and compression tests of concrete made by Fuller and Thompson, and published in their paper on Laws of Proportioning Concrete.[17] These tests cover a narrow range of strengths, but in general, they show about the same general relation as that found in Fig. 10.

Fig. 13 gives results of tests made by R. Feret[18] on mortar beams 4 by 4 by 16 cm. The relation between modulus of rupture and compressive strength is somewhat similar to that given in Fig. 10.

Flexural tests of mortars were carried out by the U. S. Geological Survey at St. Louis, 1905-08.[19]

FLEXURAL STRENGTH OF OTHER MATERIALS.

The following notes on the flexural and compressive strength of other materials than concrete may be of interest:

Marble. Tests made by the Bureau of Standards on 2¼-in. cubes in compression and beams 1½ to 2 in. deep, 3 to 4 in. wide, span 6 to 10 in. show that the modulus of rupture is uniformly about 15% of the compressive strength for marbles ranging in strength from 8000 to 28,000 lb. per sq. in. The tensile strength of marble briquets 1-in. square was about one-half the modulus of rupture. (Tech. Paper 123, Tests of Commercial Marbles, by D. W. Kessler, 1919.)

Slate. Tests made by M. O. Fuller showed modulus to vary from 75 to 100% of compressive strength. Modulus of rupture tests were made on beams 1 in. wide, 26 in. long and ¼, ½, 1 and 1½ in. deep; compression tests were made on 2-in. cubes. (Physical and Electrical Properties of Slate, Bull. Lehigh University, 1921.)

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[17]Trans. Am. Soc. Civil Eng., V. 59, p. 67, 1907.

[18]Etude Experimentale du Ciment Arme, p. 576, 1906.

[19]Portland Cement Mortars and Their Constituent Materials, by Humphrey and Jordan. Bull. 331, U. S. Geol. Survey, 1908.

Building Brick. As a result of an exhaustive series of tests carried out by the Committee on Brick of the American Society for Testing Materials, the following values were found for different classes of building brick:

Class	*Modulus of Rupture*	*Compression*	*Ratio, percent*
A	1482	8493	17.5
B	668	4171	16.0
C	621	2791	22.0
D	469	1762	27.0

Compression tests were made on whole brick, loaded flatwise; modulus of rupture tests on brick loaded flatwise on 7-in. span. (Proc. A. S. T. M., 1915, Part I.)

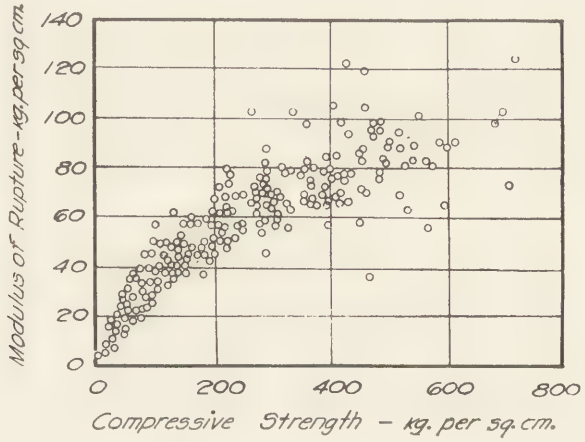


FIG. 13.—RELATION BETWEEN TRANSVERSE AND COMPRESSIVE STRENGTH OF CONCRETE. (BY FERET.)

From "Etude Experimentale du Ciment Armé," p. 576 (1906).

Gypsum. Tests made by W. A. Slater showed modulus of rupture of gypsum 43 to 52% of compressive strength; 6 by 6 by 18-in. beams and 8 by 16-in. cylinders, 35% water, age at test, 10 days. (Jl. West. Soc. Eng., Sept., 1919, p. 441.)

Cast-iron. Kirkaldy's tests on 469 samples of cast-iron showed an average modulus of rupture of 38,000 and a compressive strength of 121,000 lb. per sq. in. (ratio 31%). Modulus of rupture tests were made on bars 2 by 1 by 36-in. loaded edgewise. (Materials of Construction, by J. B. Johnson, 4th Ed., 1898, p. 447.)

Conclusions.

The tests give definite results on the flexural and compressive strength of concrete for a wide range of mixtures, consistencies, size and grading of aggregates, curing conditions, kind of aggregate, etc.

The relation between modulus of rupture and compressive strength is not uniform; for the weak mixtures the modulus of rupture is *relatively* higher than for the strong mixtures. An equation is given which expresses this relation. For usual concrete mixtures the modulus of rupture under the conditions of these tests, was about 22% of the compressive strength.

Essentially the same strength was developed by the beams loaded with top in tension and with bottom in tension; in the wetter mixtures the values were somewhat lower for bottom in tension.

Increasing the quantity of cement increased both flexural and compressive strength of the concrete. The modulus of rupture was less affected by variations in the quantity of cement than the compressive strength.

Both modulus of rupture and compressive strength of the concrete were reduced by increasing the quantity of mixing water. The modulus of rupture was less affected by the change in mixing water than the compressive strength.

With the same quantity of cement, the modulus of rupture increased rapidly as the size of the aggregate increased or the grading became coarser (up to the point where the aggregate became too coarse for the quantity of cement). The rate of increase in strength was essentially the same in beams and cylinders.

The flexural and compressive strength of concrete were affected in the same way by variations in curing condition of the concrete. The advantage of curing in damp condition was fully brought out by the tests. Curing in damp condition for 28 days gave a modulus of rupture of 48% higher than 1 day in damp condition and 27 days in dry air.

The modulus of rupture of concrete was only slightly affected by the depth of the beam. The values for beams 8 and 10 in. deep were about 4% higher than for the 4-in. beams.

There was no great discrepancy between the flexural and compressive strength of concrete made from pebbles, crushed slag and crushed limestone. Granite gave somewhat lower values, probably due to low absorption of the aggregate.

Both flexural and compressive strength of concrete cured in a damp condition until tested were proportional to the logarithm of the age.

These tests show the same relation between water-ratio and compressive strength of concrete that has been found in earlier tests. However, the relation between water-ratio and modulus of rupture was of an entirely different form.

The methods of test used in this investigation were found to give satisfactory results as shown by the uniformity of the values in the various groups of tests.

LIST OF PUBLICATIONS OF THE STRUCTURAL MATERIALS RESEARCH LABORATORY

CIRCULAR 1.—Colorimetric Test for Organic Impurities in Sands, by Duff A. Abrams and Oscar E. Harder (1917).

Out of Print.

(For a more recent discussion of this subject see, "Abrams-Harder Field Test for Organic Impurities in Sands," Proc. Am. Soc. Testing Mats., 1919, Part I; also "Tentative Method of Test for Organic Impurities in Sands for Concrete," Proc. Am. Soc. Testing Mat., 1921.)

BULLETIN 1.—Design of Concrete Mixtures, by Duff A. Abrams (1918).

BULLETIN 2.—Effect of Curing Condition on the Wear and Strength of Concrete, by Duff A. Abrams (1919).

Reprinted from the Proc. Am. Railway Eng. Assn., Vol. XX, 1919.

BULLETIN 3.—Effect of Vibration, Jigging and Pressure on Fresh Concrete, by Duff A. Abrams (1919).

Reprinted from the Proc. Am. Concrete Inst., Vol. XV, 1919.

BULLETIN 4.—Effect of Fineness of Cement, by Duff A. Abrams (1919).

Reprinted from the Proc. Am. Soc. Testing Mat., Vol. XIX, Part II, 1919.

BULLETIN 5.—Modulus of Elasticity of Concrete, by Stanton Walker (1920).

Reprinted from the Proc. Am. Soc. Testing Mat., Vol. XIX, Part II, 1919.

BULLETIN 6.—Effect of Storage of Cement, by Duff A. Abrams (1920).

BULLETIN 7.—Effect of Tannic Acid on the Strength of Concrete, by Duff A. Abrams (1920).

Reprinted from the Proc. Am. Soc. Testing Mat., Vol. XX, Part I, 1920.

BULLETIN 8.—Effect of Hydrated Lime and Other Powdered Admixtures in Concrete, by Duff A. Abrams (1920).

Reprinted from the Proc. Am. Soc. Testing Mat., Vol. XX, Part II, 1920.

BULLETIN 9.—Quantities of Materials for Concrete, by Duff A. Abrams and Stanton Walker (1921).

BULLETIN 10.—Wear Test of Concrete, by Duff A. Abrams (1921).

Reprinted from Proc. Am. Soc. Testing Mat., Vol. XXI, 1921.

BULLETIN 11.—Flexural Strength of Plain Concrete, by Duff A. Abrams (1922).

Reprinted from the Proc. Am. Concrete Inst., Vol. XVIII, 1922.

Bulletin 12

Structural Materials Research Laboratory
Lewis Institute
Chicago

Tests of Impure Waters for Mixing Concrete

By

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FOREWORD

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TESTS OF IMPURE WATERS FOR MIXING CONCRETE.

By Duff A. Abrams.

SUMMARY AND CONCLUSIONS.

Strength tests of portland cement concrete were made at ages of 3 days to 2 1/3 years using mixing waters of a wide range of types, many of which were thought to be unsuitable for use in concrete. Sixty-eight samples of water were tested in two different investigations; 38 samples were collected from different sections of the country; 18 were from the Chicago district; the remaining 12 samples were distilled waters, synthetic sea water and solutions of common salt. Among the waters tested were sea and alkali waters, bog waters, mine and mineral waters, waters containing sewage and industrial wastes, and solutions of common salt. Tests of fresh waters (including distilled) were made for purpose of comparison. About 6000 tests are included in this report. Reference is made to a number of other investigations on related subjects.

Series 137.—50 samples of water were used in 1: 4 concrete of relative consistency 1.10 and tested after curing under the following conditions:

(a) Moist room, tested at ages of 3 days to 2 1/3 yr.,

(b) Moist room 28 days, then in air of laboratory, tested at 3 mo. to 2 1/3 yr.

Series 138.—18 samples including sewage and trade wastes from the Chicago district, were used in concrete cured in moist room as follows:

(a) 1: 7, 1: 5, 1: 4, 1: 3 and 1: 2 mixtures, relative consistency 1.00, tested at 28 days.

(b) 1: 4 concrete mix, relative consistency 0.90, 1.00, 1.10, 1.25, and 1.50, tested at 28 days.

(c) 1: 4 concrete mix; relative consistency 1.00, tested at 3, 7, and 28 days, 3 mo., 1 and 2 1/3 yr.

(d) 1: 3 standard sand mortar, tension tests of briquets and compression tests of 2 by 4-in. cylinders at ages given in (c).

Concrete and mortar tests were made in accordance with standard methods. In general, 5 to 10 concrete specimens, and 5 mortar specimens were made in a set on different days.

Time of setting and soundness tests of cement were made with each sample of mixing water.

The principal conclusions from these tests are:

(1) In spite of the wide variation in the origin and type of the waters used, and contrary to previously accepted opinion, most of the impure waters gave good results in concrete, probably due to the fact that the quantity of injurious impurities present was quite small. The following samples gave concrete strengths below the strength-ratio of 85 per cent which was considered the lower limit for acceptable mixing waters: Acid waters, lime soak from tannery, refuse from paint factory, mineral water from Colorado, and waters containing over 5 per cent of common salt.

(2) The quality of a mixing water is best measured by the ratio of its 28-day concrete or mortar strength to that of similar mixes with fresh water. While the lowest permissible strength-ratio is a matter of judgment, waters giving strength-ratios which in general fall below 85 per cent should be considered unsatisfactory; if only isolated tests are made, 80 per cent should be the limiting value. The time-of-setting test appears to be an unsafe guide as to the suitability of a water for mixing concrete.

(3) Neither odor nor color are any indication of quality of water for mixing concrete. Waters which were most unpromising in appearance, gave good results. It may safely be said, however, that any natural water which is suitable for drinking can be used without question for mixing concrete.

(4) Distilled water gave concrete strengths essentially the same as other fresh waters.

(5) Bog waters which were thought to be unsuitable for mixing concrete generally contained only small quantities of foreign materials and gave good results. The strength-ratios for the individual samples were seldom below 90 per cent.

(6) Sulphate waters produced little or no ill effects until a SO_4 concentration of about 1 per cent was reached. For a concentration of 0.5 per cent the average reduction in strength was about 4 per cent; a concentration of 1 per cent was required to produce a reduction in strength of more than 10 per cent.

(7) Concrete mixed with sea water (about 3.5 per cent salts, mostly sodium chloride) and cured in the moist room gave higher strengths than fresh-water concrete at ages of 3 and 7 days; at 28 days and over, the strength-ratios for sea water ranged from 80 to 88 per cent. Air-cured concrete mixed with sea water was lower in strength than similar fresh-water concrete at 3 mo., but showed a recovery in strength at later ages and gave strengths equal to that obtained with fresh water. (In spite of the satisfactory strength results, it seems unwise to use sea water in reinforced-concrete construction, particularly in the tropics on account of danger of corrosion of reinforcement.)

(8) Synthetic sea water gave concrete and mortar strengths similar to natural sea water.

(9) Concrete mixed with water from the Great Salt Lake (about 20 per cent sodium chloride) gave strength-ratios from 65 to 77 per cent at ages of 28 days and over. This water is not satisfactory for mixing concrete, unless allowance is made for about 30% reduction in strength.

(10) Water from Devil's Lake, North Dakota (0.15 per cent sodium sulphate and 0.15 per cent sodium chloride), gave normal concrete strengths and showed no ill effects.

(11) Water from Medicine Lake, South Dakota (3.5 per cent solution of sulphates, largely magnesium; SO_4 concentration 2.8 per cent), gave strengths similar to that obtained with sea water. The lowest strength-ratio was 84 per cent.

(12) Waters from drains and small streams in sulphate districts gave satisfactory strengths at ages up to 2 1/3 yr. The lowest strength-ratios were about 90 per cent.

(13) Concrete made with solutions of common salt and cured until test in a moist room showed a slight increase in strength at 3 days for solutions of 10 per cent and less. Solutions of low concentration (1 and 2 per cent) also showed a slight increase in strength at 7 days; after 7 days, however, all concentrations gave material reductions in strength. Strength-ratios as low as 60 per cent were found for a 20 per cent solution at early ages and for 10 per cent and 15 per cent solutions at the later ages. Concrete made with salt solutions and cured in the moist room for 28 days, then in air, gave results at 3 mo. almost identical with that obtained for moist-room curing. For this curing condition, the addition of salt reduced the strength at 1 yr. about 12 per cent; at 2 1/3 yr. there was no reduction in strength. The apparently conflicting results for moist-room and air-curing have not been explained.

(14) The use of common salt for the purpose of lowering the freezing point of the mixing water during cold weather should not be permitted; 5 per cent of salt lowers the freezing point of water about 6° F., but reduces the strength of concrete about 30 per cent.

(15) Mine and mineral waters gave good results in concrete, with the exception of a carbonated mineral water from Colorado which gave strength-ratio as low as 80 per cent. Pumpage waters from coal and gypsum mines also gave good results in concrete.

(16) Water containing sanitary sewage gave essentially the same concrete strength as fresh water. Water from the Illinois River, which carries sewage from Chicago, gave strength-ratios at 28 days and 3 mo. of 83 and 85 per cent for moist-room curing; for air-curing strength-ratios ranged from 92 to 102 per cent.

(17) Waters containing refuse from oil refineries gave erratic strengths. These samples generally gave strengths near normal, but in some cases material reductions in strength were found. Setting time of cement with one water sample was, initial 10 hr., final 42 hr.

(18) "Bubbly Creek" water, which was highly polluted with wastes from the Chicago Stockyards and gave off an offensive odor showed strength-ratios of about 100 per cent for all ages, mixes and consistencies.

(19) Tannery wastes generally gave reductions in concrete strength; the lowest strength-ratios were about 80 per cent (lime soak water).

(20) Brewery and soap works wastes gave concrete strengths essentially the same as that of fresh water.

(21) Waste from a gas plant and a corn products factory gave good results; the strength-ratios ranged from 90 to 100 per cent.

(22) Paint factory waste water gave strength-ratios from 80 to 90%.

(23) A spent plating bath containing sulphuric acid, after dilution to 10 and 20 per cent of its original concentration, gave strength-ratios as low as 85 per cent for the 10 per cent solution and 75 per cent for the 20 per cent solution. For different consistencies both solutions gave about the same strength-ratios which ranged from 88 to 106 per cent. Lower strength-ratios were obtained with the rich concretes than with the lean.

(24) The strength of concrete mixed with all samples of impure waters showed normal increase at 28 days with additional quantities of cement.

The impure waters gave about the same strength-ratios regardless of the mix used in the concrete tests. For the usual range in mixtures (1:5 to 1:4) the strength increased about 1 per cent for each 1 per cent additional cement.

(25) There was a marked reduction in strength of concrete with increase in quantity of mixing water for both fresh and impure waters. Increasing the quantity of mixing water 1 per cent reduced the strength of concrete about the same amount as if the quantity of cement were *reduced* 1 per cent. A comparatively slight increase in *quantity* of mixing water produced a greater reduction in concrete strength than that caused by the use of the *most polluted* mixing water that is ordinarily encountered. These tests show the importance of the water-ratio strength relation in concrete which has been pointed out in numerous other reports from this Laboratory.

(26) The effect of impure waters was in general independent of the consistency of the concrete. Acid waters from a spent plating bath gave somewhat higher strength-ratios in the wetter concretes.

(27) The strength of concrete cured in a damp condition at normal temperatures increased with age for both fresh and impure waters. The strength was approximately proportional to the logarithm of the age at test.

(28) The effect of impure mixing waters on the tensile and compressive strength of 1:3 standard sand mortar at ages of 3 days to 2 1/3 yr. was generally similar to that on the compressive strength of concrete. In the mortar tests a few waters gave somewhat higher strength-ratios and one water gave a somewhat lower strength-ratio than was obtained in concrete.

(29) The percentage of water required for normal consistency of cement when mixed with the impure water was, with a few exceptions, about the same as for fresh waters. Water from Great Salt Lake, solutions of 5 to 20 per cent of common salt, refuse from an oil refinery, Medicine Lake water, and acid water from a spent plating bath, required somewhat higher percentages for normal consistency than fresh water.

(30) The time of setting of portland cement mixed with the impure waters was about the same as for fresh waters; however, there were some notable exceptions. In most instances the samples giving low concrete strength-ratios were slow setting. On the whole the tests show that time of setting is not a satisfactory test for suitability of a water for mixing concrete.

(31) None of the impure waters caused unsoundness of the portland cement when subjected to the standard test over boiling water.

(32) Most specifications for water for mixing concrete are so worded that they would, if strictly enforced, exclude nearly all but rain water and distilled water; these tests have shown that almost any impurity may be present without *necessarily* producing ill effects. The important point is not whether impurities are present, but do the impurities occur in *injurious* quantities?

(33) The effect of sugar and similar compounds was not studied; earlier tests have shown that these compounds are most detrimental and must be avoided.

TESTS OF IMPURE WATERS FOR MIXING CONCRETE.

By Duff A. Abrams.

INTRODUCTION.

Water is one of the essential constituents of concrete, hence it is important to establish the effect of both *quantity* and *quality* of mixing water on the strength and other properties of concrete. Tests made in this and other laboratories have shown the effect of *quantity* of mixing water; the present investigation covers an experimental study of the effect of *quality* of mixing water.*

In many sections of the country the possibility of building concrete structures, especially concrete roads, may depend on the suitability of the local waters which may be contaminated with various impurities; alkali waters, bog waters, and waters containing sewage, mine pumpage, or other trade wastes are characteristic of many important industrial districts.

A few tests from other sources have been reported on the effect of sewage on the strength and time of setting of cement; many tests have been made using sea water. Earlier tests were limited in number and scope; they were in general made on cement or sand mortar briquets, hence gave little direct information on the concrete-making quality of the waters. This appears to be the first comprehensive study of the effect of impure mixing waters on the strength of *concrete.*

68 separate samples of water were tested in two different series of investigations. 38 samples were collected from many sections of the country. 18 of the samples were from the Chicago district; the remaining 12 samples included distilled waters, synthetic sea water and solutions of common salt. In general the waters were of a nature which was believed to be unsatisfactory for mixing concrete. Parallel tests were made on several samples of clean, fresh waters. The samples may be classified as follows:

Fresh, clean waters (in general potable);
Minnesota bog waters;
Sea and alkali waters;
Mine and mineral waters;
Water contaminated with sewage and industrial wastes;
Solutions of common salt.

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*See following reports for the effect of *quantity* of mixing water:—

Effect of Consistency on Strength of Concrete; Jl. Am. Concrete Inst., Oct.-Nov., 1914.

Strength and Other Properties of Concrete, by Wig and others; Technologic Paper 58, U. S. Bureau of Standards, 1916.

Effect of Grading of Sands and Consistency of Mix upon the Strength of Plain and Reinforced-Concrete, by L. N. Edwards; Proc. Am. Soc. Testing Materials, Part II, 1917.

Strength of Concrete; Its Relation to the Cement, Aggregates and Water, by Talbot and Richart; Bulletin 137, Eng. Experiment Station, Univ. of Ill., 1923.

Bulletins 1, 2, 5, 8, and 11 of the Structural Materials Research Lab.

Economic Value of Admixtures, by Pearson and Hitchcock; Proc. Am. Concrete Inst., 1924.

The tests described in this paper were confined to the use of impure waters in mixing concrete; the use of impure waters for curing concrete was not studied.

These tests were a part of the experimental studies of the properties of concrete and concrete materials being carried out through the co-operation of Lewis Institute and the Portland Cement Association at the Structural Materials Research Laboratory, Lewis Institute, Chicago.

OUTLINE OF TESTS.

This report includes two series of tests and gives the results of about 6000 strength tests of portland cement concrete and mortar. Series 137 was confined to a 1:4 concrete using 50 separate samples of water; in Series 138, 18 separate samples were used in concrete of a wide range of mixes and consistencies. In both series concrete tests were made at ages of 3 days to 2 1/3 yr.

Series 137.—(Specimens made Aug. to Nov., 1920) consisted of compression tests of about 2200 4 x 8-in. concrete cylinders using 50 different samples of mixing water. A description of the waters is given in Table 1, chemical analyses in Table 2.

Tests of 1:4 concrete, relative consistency 1.10 were made for the following curing conditions: (Table 10)

(a) Moist room until tested at 3, 7 and 28 days, 3 mo., 1 and 2 1/3 yr.
(b) Moist room 28 days, remainder in air tested at 3 mo., 1 and 2 1/3 yr.

Time of setting and soundness tests of the cement using each mixing water are given in Table 8. Miscellaneous tests of cement and aggregates are given in Tables 5 to 7.

In general each value of concrete strength is the average of 5 or 6 tests made on different days.

Series 138.—(Specimens made April and May, 1921). This series included tests on 18 different waters most of which were from the Chicago district. Compression tests were made on about 2700 6 x 12-in. concrete cylinders, 540 (each) 2 x 4-in. standard-sand mortar cylinders and briquets. A description of the water samples is given in Table 3; chemical analyses in Table 4.

Tests were made as follows:

(a) Concrete, 1:7, 1:5, 1:4, 1:3 and 1:2 mixes by volume; relative consistency 1.00; age at test 28 days. (Table 11.)
(b) Concrete, 1:4 mix; relative consistency 0.90, 1.00, 1.10, 1.25 and 1.50; age at test 28 days. (Table 12.)
(c) Concrete, 1:4 mix; relative consistency 1.00; age at test 3, 7 and 28 days, 3 mo., 1 and 2 1/3 yr. (Table 13.)
(d) Briquet and 2 x 4-in. cylinder tests of 1:3 standard sand at ages given under (c). (Table 14.)
(e) Time of setting and soundness tests of the cement were made using each mixing water. (Table 9.)

All concrete specimens were cured in moist room until test; mortar cylinders and briquets were cured in water after the first 24 hr. and tested at the ages given above.

The strengths of concrete given in the tables are the average of 10 tests made on different days; for the mortar, 5 tests.

MATERIALS.

Water.—39 of the 50 samples of water in Series 137 were collected in about 10-gal. lots. About 50-gal. lots of 13 different waters representing what were considered the worst qualities to be found in the Chicago district were collected for test in Series 138. The solutions of common salt and the synthetic sea waters were prepared at the Laboratory; the distilled waters were purchased in Chicago; the Lake Michigan waters were from the city water supply. For details of the water samples see Tables 1 to 4.

Portland Cement consisted of a mixture of equal parts of 5 brands purchased in Chicago. About the first two-thirds of the specimens in Series 137 were made from Cement Lot 4951, and the remainder from Cement 5075. In Series 138, concrete and mortar tests were made from Cement 5259. Chemical analyses of the cements are given in Table 5; standard-sand mortar tests of the cements using Lake Michigan water are given in Table 6.

Aggregate for concrete tests in both series consisted of sand and pebbles from Elgin, Ill. For Series 137 the aggregate was graded 0 to ¾-in.; for Series 138, 0 to 1½-in. In order to secure a uniform grading of aggregate, the sand and pebbles were separated into the following sizes and recombined to the sieve analyses shown in Table 7: 0-No. 4; No. 4-⅜ in.; ⅜-¾; ¾-1½.

TEST PIECES.

In Series 137 the strength tests were made on 4 x 8-in. concrete cylinders; in Series 138, on 6 x 12-in. cylinders. In Series 138 compression tests were made on 2 x 4-in. cylinders and tension tests on briquets of 1:3 standard sand. Concrete specimens were made, cured and tested in accordance with "Tentative Methods of Making Compression Tests of Concrete" (Serial Designation: C39-21T) of the American Society for Testing Materials; mortar specimens in accordance with the Standard and Tentative Specifications of the American Society for Testing Materials.

The concrete mixtures were expressed in terms of 1 volume of cement to a given number of volumes of aggregate, *dry and rodded* after combining to the grading used. Concrete was mixed by hand with a blunted trowel in metal pans in batches of sufficient size for three 4 x 8-in. cylinders or one 6 x 12-in. cylinder.

The quantity of mixing water was the same for similar concrete, except insofar as differences in normal consistency of the cement dictated small variations. The plasticity of the concrete was measured by means of the

"flow-table".* The flow-table consists of a circular metal plate attached to a frame in such a way that it can be raised and dropped by means of a cam. The test is made by rodding the freshly-mixed concrete into the mold on the metal table. The mold consists of a truncated metal cone (top diameter 6¾ in., bottom diameter 10 in., height 5 in.). After the mold is filled, it is immediately withdrawn and the table raised and dropped ½ in., 15 times in about 10 seconds. The base diameter of the mass of concrete after the test, expressed as a percentage of the original diameter, is the "flow."

The concrete cylinder forms were of cold-drawn steel tubing, slotted along one element. In making the specimens the forms were placed on machined cast-iron plates. The concrete was placed in 3 layers, each layer being rodded 30 times with a ⅝-in. bullet-pointed steel rod. Three to four hours after making, the specimens were capped with neat cement (which had been allowed to stand 3 to 6 hr. after mixing) and the cap made plane by means of a machined plate which was worked down to the top of the form.

The forms were removed after 16 to 20 hr. and the specimens placed in the moist room. In general they remained in the moist room until test; for a portion of Series 137 they were cured in air after 28 days in the moist room.

Concrete tests were made in a 200,000-lb. universal testing machine. The load was applied through a spherical bearing block placed on top of the cylinder.

DISCUSSION OF TESTS.

The results of the strength tests of concrete and mortar are given in Tables 10 to 22 and Figs. 1 to 7. The most striking feature of this investigation was that in spite of the wide range in type of mixing waters, the samples, with a few exceptions, gave good results in concrete.

The waters used ranged from distilled water to water containing nearly 250,000 parts per million of solids. The impurities consisted of alkaline salts, sewage, industrial wastes of various kinds and miscellaneous salts, minerals and other impurities found in mines, deep wells, bogs, etc.

The following discussion points out briefly the principal features of these tests. Chief emphasis is placed on the results of tests of the 1:4 concrete; this mix was used throughout Series 137 and in the bulk of the tests in Series 138 and represents the quality of concrete used in road construction and other high-grade work.

Criterion of Quality of Mixing Water.—In this discussion the quality of mixing water will be measured by comparing its concrete strength with that of fresh water tested at the same time, in the same mix, at the same

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*See "Measuring Flowability of Concrete by Flow Table," Concrete, June, 1920, v. 16, p. 274; Eng. News-Rec., May 27, 1920, p. 1044.

Time of Set of Concrete, by Watson Davis; Proc. Am. Soc. Testing Materials, v. 21, p. 995, 1921.

Economic Value of Admixtures, by Pearson and Hitchcock; Proc. Am. Concrete Inst., 1924.

age, etc. The "strength-ratios" computed on this basis are given in the tables. While the lowest permissible strength-ratio is a matter of judgment, we have considered that waters which give strength-ratios less than 85 per cent were unsatisfactory for mixing concrete. This is a rigid requirement, since some allowance must be made for accidental variations in the tests. Such a rigid requirement is justified in this discussion only because we have made a large number of tests at the same time, under carefully controlled conditions. Where isolated tests of concrete or mortar are relied upon, the limiting strength-ratio should be reduced to 80 per cent or 75 per cent.

The following waters gave concrete strength-ratios below 85 per cent, hence are considered unsatisfactory:

Acid waters,
Lime soak from tannery,
Refuse from paint factory,
Waters containing over 5 per cent of common salt,
Mineral water from Montrose, Colorado.

Fresh waters were collected from city supplies and rivers and were such as would usually be accepted without question for mixing concrete. In Series 137, 8 samples may be so classified. Tests on Lake Michigan and distilled water were repeated in different portions of the investigations.

Considerable difficulty was experienced in classifying some of the samples; for instance, Sample 37 from Youghiogheny River, Pa., was said to contain sewage and industrial wastes, but the analysis showed it to be remarkably free from impurities, hence it was grouped with the fresh waters.

In each series the *average* strength of concrete made from the fresh waters was used as a basis for studying the values from impure waters (Table 15). The percentages secured in this way are referred to as the "strength-ratios" of the concrete for a given mix, age, curing condition, etc.

The two series have one group of tests in which the concrete was quite similar, that is, the 1:4 mix, relative consistency 1.10, tested at 28 days; strengths of 3080 and 3350 lb. per sq. in. were obtained for Series 137 and 138, respectively. This is a satisfactory agreement, considering that a smaller size of test piece and a smaller aggregate were used in the first series, and that the concrete was mixed from different lots of materials about 9 mo. apart.

The higher strengths in Series 138 (Table 15) may be attributed principally to the drier consistency used.

The 8 different samples of fresh water in Series 137 gave essentially the same results throughout the period covered by the tests, that is, 3 days to 2 1/3 yr.; the mean variation of the samples from the average was about 5 per cent.

Distilled Water gave concrete strengths essentially the same as other fresh waters; the slight discrepancies which occur in a few instances may be attributed to accidental variations in the tests.

Impure Waters.—Comments on a given type of water are grouped together and refer to both series of tests. In general comparisons are made on the basis of the *strength-ratios* as compared with the *average* of the fresh waters used in the same mixes, etc., in the same series.

The average concrete strengths and strength-ratios of each of the 6 groups of waters tested at different ages in Series 137 are plotted in Fig. 3. Similar data for each of the samples in Series 138 are shown in:

Fig. 4 Effect of Quantity of Cement,
Fig. 5 Effect of Consistency of Concrete,
Fig. 6 Effect of Age of Concrete.

Bog Waters.—7 samples of bog waters which were thought to be unsuitable for mixing concrete were collected in Minnesota. The chemical analyses of these waters showed only small quantities of foreign matter; the total solids was frequently lower than in Lake Michigan water. In general, these waters gave good results in concrete at all ages (See Table 10 and Fig. 3). The average strengths for individual waters did not often vary more than 10 per cent from the average for the fresh waters. The mean variation from the average concrete strength for the fresh waters at a given age was about 6 per cent.

Alkali Waters include all the samples in Group 3 and 4 of Series 137, synthetic sea water and water from Medicine Lake in Series 138. For convenience the discussion of the tests will be presented under the following headings; sea water, synthetic sea water, Great Salt Lake, Devil's Lake, Medicine Lake, waters from tile drains and small streams in sulphate districts and solutions of common salt. Some of the mine and mineral waters (Group 5, Series 137) showed a higher sulphate content than certain samples in Group 3, but it seemed best to preserve this classification.

Sea Water.—Series 137 included tests on 2 samples of sea water collected from different points on the New Jersey coast. These samples were handled separately throughout. The average strength-ratios are given in Table 16. For sake of comparison the values for synthetic sea water are included.

Sea water (and synthetic sea water) had an accelerating effect on the early hardening of concrete as shown by the strength-ratios of 124 per cent to 137 per cent at 3 days. At an age of about 10 days, the strength was equal to that of fresh water; from 28 days to 2 1/3 yr., the strength-ratios ranged from 80 to 88 per cent for moist-room curing. The specimens cured in moist room for 28 days and remainder in air showed a decided recovery as indicated by the strength-ratios of 88, 100, and 96 per cent at 3 mo., 1 and 2 1/3 yr. Sea water gave normal results in the time of setting tests.

Synthetic Sea Water.—A 3.5 per cent solution of salts consisting principally of sodium chloride and magnesium sulphate in fresh water is frequently used in experimental work as a substitute for natural sea water. (For analysis, see Tables 2 and 4.) The parallel tests for moist-room curing in Series 137 and 138 showed a close agreement considering that different lots of materials were used, etc. The specimens cured in air

showed about the same increase in strength-ratios as the natural sea water. Tables 11 and 12 show that neither mix (quantity of cement) nor the consistency of the concrete (quantity of mixing water) exerted much influence on the strength-ratios of concrete made from synthetic sea water at 28 days. The strength-ratios are summarized in Table 16. Synthetic sea water produced the same effect in concrete as natural sea water.

Numerous instances are on record in which sea water was used in mixing concrete with apparently good results; however, experienced engineers are practically unanimous in the belief that sea water should not be used for mixing in *reinforced-concrete work*, particularly in the tropics.*

Great Salt Lake Water (Sample 5) contained about 20 per cent of salts in solution. Analyses of this water reported by different authorities show concentrations ranging from 14 to 27 per cent.† In general the salts consisted of sodium chloride, although magnesium and calcium salts and sulphates were present. The strength-ratios were 112, 91, 77, 76, 71 and 65 per cent at 3, 7 and 28 days, 3 mo., and 1 and 2 1/3 yr., respectively. This water is not considered satisfactory for mixing concrete, unless we take into account the fact that the concrete strength will be reduced to about 70 per cent of normal.

Devil's Lake Water, N. D. (Sample 26) contained about 0.4 per cent of salts in solution, largely sodium sulphate and sodium chloride in about equal amounts. This water gave strength-ratios of 102, 107, 99, 96, 98 and 90 per cent for the ages mentioned above.

Medicine Lake Water, S. D. (Sample 105) consisted of about 3.5 per cent solution of sulphates, largely magnesium and gave strengths about the same as sea water. The strength-ratios were 110, 102, 88, 84, 88 and 92 per cent.

Waters from Tile Drains and Small Streams in Alkali Districts.—Samples of water from tile drains and small streams were collected in the alkali districts of Minnesota, Colorado, Utah and New Mexico. (5 samples from Group 3, Series 137.) The SO_4 content of these waters ranged from 1060 to 7700 parts per million. These samples gave satisfactory concrete strengths at ages up to 2 1/3 yr.; the average strength-ratios were 115, 103, 99, 98, 100 and 94 per cent. The values for air-curing were somewhat higher than for moist-room curing. The lowest values were found for Samples 31 and 46 from Utah.

Effect of SO_4 Content of Mixing Water.—In Fig. 1 a study has been made of the relation between the strength of 1:4 concrete and the SO_4

*See "Concrete Viaducts on the Key West Extension of the Florida East Coast Railway," by G. P. Carver; Eng. Record, Oct. 20, 1906.

"Bad Effects Resulting from Use of Salt Water in Reinforced-concrete Structures Built in Tropical Countries," by J. L. Harrison; Abstract Eng. News, v. 76, p. 1047, Nov. 30, 1916.

†"Data of Geochemistry," by F. W. Clarke, Bull. 695, U. S. Geological Survey, 1920.

content of the mixing water for all the samples in Series 137. The diagram shows that, on the whole, little or no ill effects were produced by sulphates until the concentration of SO_4 in mixing water reached 1.0 per cent. For 0.5 per cent the average reduction in strength as shown by the curves was 4 per cent; a concentration of 1 per cent (10,000 parts per million) was required to produce a reduction in strength of concrete of more than 10 per cent.

Solutions of Common Salt.—Tests were made using solutions of common salt (sodium chloride) in concentration up to 20 per cent as mixing water. Tests were made at ages of 3, 7 and 28 days, 3 mo., 1 and 2 1/3 yr. for specimens cured in moist room and at ages of 3 mo., 1 and 2 1/3 yr. for specimens cured 28 days in moist room and remainder in air. Concentrations of 1 and 2 per cent of common salt produced a slight increase in strength at early ages; at later ages the strength-ratios were below "par," even for these low concentrations. Data of the tests are plotted in Figs. 2 and 3. There was quite a wide difference due to curing conditions. For moist-room curing, even for the low concentrations, the strength-ratios decreased rapidly as the concentration was increased and as the age at test increased. Concentrations of 5, 10, 15 and 20 per cent salt, gave strength-ratios at 28 days of 75, 68, 65 and 61 per cent; the ratios at ages of 3 mo. to 2 1/3 yr. were in general still lower.

The tests on air-cured specimens gave results at variance with those secured for moist-room curing; at ages of 1 and 2 1/3 yr. the strengths for air-curing compared favorably with those for the fresh water.

There is an old rule for concrete work in cold weather to the effect that freezing of concrete can be prevented by adding to the mixing water 1 per cent of salt for each degree Fahrenheit below the freezing point. Such a rule is to be found in many text-books published during the past 40 years.*

The following values† indicate the freezing point of water containing different quantities of common salt:

Salt in Water Per Cent by Weight	Freezing Point of Solution °F.	Strength-Ratios of Concrete	
		7 days	28 days to 2 1/3 yr.
0	32.0	100	100
1	30.5	104	93
2	29.3	103	85
5	25.2	94	72
10	18.7	84	66
20	6.1	75	60

*This rule is attributed to Tetmajer, by Taylor and Thompson; see "Concrete Plain and Reinforced," 1916, p. 287.

†"Mechanical Engineers Handbook," by Marks.

4 to 6. For all mixes, consistencies and ages the concrete strengths were essentially the same as that produced by fresh water. Judged by any of the usual standards, this water, prior to these tests, would not have been considered acceptable for mixing concrete, yet the tests show it to give good results.

Brewery Waste (Sample 107) gave concrete strengths almost identical with fresh water for different mixes and consistencies at 28 days and for the 1: 4 mix at different ages.

Soap Works Waste (Sample 109) gave concrete strengths almost identical with that of fresh water.

Gas Plant Waste.—Water used to seal gas machines (Sample 110) gave strength-ratios of about 95 per cent.

Waste from Corn Products Refining Co. (Sample 111) gave strengths which compared favorably with fresh waters. In no case were the strength-ratios below 90 per cent and averaged 94 per cent (Table 20).

Paint Factory Waste (Sample 116, see Table 21 and Fig. 4 to 6) gave strength ratios ranging from 79 per cent to 90 per cent, average about 86 per cent. The low strength from this water is probably due to the presence of acid.

Acid Water from a spent plating bath (Sample 117) contained sulphuric acid in such a high concentration that it was necessary to dilute it to 10 and 20 per cent of its original concentration by the addition of Lake Michigan fresh water before it could be used for mixing concrete. The effect of this water varied considerably with the concentration and the characteristics of the concrete with reference to quantity of cement, mixing water, etc. The 1: 7 mix at 28 days showed strength-ratios of 108 and 120 per cent while the 1: 2 mixtures gave strength-ratios of about 86 per cent. For the usual consistencies and mixtures the strength-ratio was about 90 per cent. The water required for normal consistency of cement using the acid waters was 26 and 27 per cent as compared with 24 per cent for fresh water. The time of setting of the cement with these waters was in general somewhat longer than for fresh water.

Effect of Quantity of Cement (Mix).—Fig. 4 shows the relation of the 28-day strength and strength-ratios to quantity of cement for 1: 7 to 1: 2 concrete mixes of relative consistency 1.00 for the waters in Series 138. In all cases there was an increase in strength with increase in amount of cement. The strength-ratio curves are in general horizontal or nearly so, showing that the effect of the various impure waters was similar for the different mixes. The acid waters from a spent plating bath (Sample 117) gave greater reductions in strength in the rich mixes than in the lean.

Effect of Quantity of Mixing Water (Consistency).—The effect of consistency on the 28-day strength of 1: 4 concrete mixed with 15 different samples of water in Series 138 is shown in Fig. 5. The strength curves show the marked effect of quantity of mixing water on the compressive strength of concrete mixed with both fresh and impure waters.

The individual strength-ratio curves are in general horizontal showing that the effect of the impure waters was the same, regardless of the consistency of the concrete. The strength-ratio curves for acid waters from a spent plating bath (Sample 117) have an upward trend, showing that the effect of these waters was somewhat less in the wetter concretes. The *average* strength-ratio curve for all impure waters was approximately horizontal.

Fig. 7 shows the relation of quantity of mixing water, as expressed by the water-cement ratio and gallons per sack of cement to the 28-day compressive strength for the fresh waters in Series 138. In these tests the quantity of mixing water was varied by

(a) Change in mix (relative consistency 1.00 (Table 11).
(b) Change in consistency (1: 4 mix, Table 12).

All of the plotted points for the two conditions of test lie close to the curve, showing remarkably consistent results. Similar curves may be drawn for the impure waters in Series 138.

These tests show the importance of the water-ratio-strength relation which has been pointed out in many other reports from this Laboratory. The relation between strength and quantity of mixing water for *fresh waters* is shown below:

Relative consistency ...	0.90	1.00	1.10	1.25	1.50
Water-ratio	0.68	0.75	0.82	0.92	1.09
Gallons of water per sack of cement	5.1	5.6	6.2	6.9	8.2
Concrete Strength at 28 days, lb. per sq. in. ...	4200	3680	3350	2580	1190
Strength-ratio to Consistency 1.00	114	100	91	70	43
Strength-ratio to Consistency 1.10	126	110	100	77	47

In computing water-ratios, absorption of aggregates was disregarded. 6.2 gal. of water per sack of cement (water-ratio 0.82) is about the best consistency for concrete road construction; adding 0.7 gal. per sack of cement had the effect of reducing the strength of concrete to such an extent as to give a strength-ratio of 77 per cent.

Increasing the quantity of mixing water produced exactly the same effect as *reducing* the quantity of cement in the batch. (See Fig. 7.) A 1: 4 mix with relative consistency 1.25 (25 per cent more water than "normal" consistency) gave about the same strength at 28 days as a 1: 6 mix of normal consistency; a 1: 4 mix with relative consistency 1.50 gave a lower strength than a 1: 7 mix of normal consistency. A relative consistency of 1.50 is by no means as "sloppy" as concrete frequently seen.

A comparatively slight increase in *quantity* of mixing water may produce a greater reduction in concrete strength than that caused by using the *most polluted* mixing water that is ordinarily encountered.

Effect of Age.—The effect of age on the strength of concrete is shown in Tables 10, 13 and 15, and in Fig. 3 and 6. The results of tests in Series 137 are given in Fig. 3 in which age is plotted to a logarithmic scale.

Separate curves are shown for the average of each group of waters for two methods of curing.

Fig. 6 shows the effect of age for the different waters in Series 138. The curves show that unusually consistent results were obtained with each water. In general there was an increase in strength with age for each of the waters used. The strength-ratio-age curves show the relation of strength of concrete made with impure waters as compared with that of similar concrete made with fresh water at the different ages.

Strength-ratios for the fresh waters in the two series, based on the 28-day tests of concrete for specimens cured in the moist room were as follows:

	3 days	7 days	28 days	3 mo.	1 yr.	2 1/3 yr.
Series 137	31	52	100	141	177	167
Series 138	33	57	100	144	163	176

It will be noted that the 1-yr. tests in Series 137 appear to be abnormally high; this may account for the apparent retrogression in the 2 1/3 yr. tests in this Series.

For concrete cured in a damp condition, the strength is approximately proportional to the logarithm of the age at test.

Specimens in Series 137 cured in moist room for 28 days and then in air gave approximately the same strengths at 3 mo. as similar concrete cured in moist room for 3 mo.; at 1 and 2 1/3 yr. air-cured specimens showed a falling off in strength, except in the case of 5 to 20 per cent salt solutions, where increases in strength were generally found.

In Series 138, synthetic sea water (Sample 104), paint manufacturing waste (116), acid waters from a spent plating bath (117) and lime soak (115) gave strength-ratios, in certain instances below the 85 per cent which we have set as the lower limit for acceptable mixing waters. It is interesting to note that the *average* concrete strength for all impure waters in this series was essentially the same as for fresh waters.

The 28-day strength of concrete or mortar seems to be the best indication of quality of mixing water. In a few instances the 3 and 7-day strengths were abnormally high or low. In no instance in the moist room-cured specimens, does the later tests give results which are materially at variance with those at 28 days.

Mortar Tests.—Results of tension and compression tests of 1: 3 standard sand mortars at ages of 3 days to 2 1/3 yr. for the waters in Series 138 are given in Table 14. A comparison of these strength-ratios with those for the concrete tests in Table 13 shows that in general the effect of the impure waters on *mortar strength* was similar to that on the concrete strength at different ages. The mortar strength-ratios of synthetic sea water, Medicine Lake, paint manufacturing waste and acid waters from a spent plating bath were generally somewhat higher at all ages than the strength-ratios of the concrete tests. The strength-ratios for briquet tests of 1-3 standard sand mortar mixed with water from "Bubbly Creek" were somewhat lower than the strength ratios for the compression tests of mortar and concrete.

Normal Consistency.—The percentage of water required for normal consistency of cement when mixed with the different impure waters was in general about the same as for fresh waters. In Series 137 the average normal consistency for the fresh water was 22.5 per cent. Great Salt Lake water (Sample 5) required 24 per cent; solutions of 5 to 20 per cent of common salt required from 24 to 25 per cent. Refuse from an oil refinery (Sample 40) required 25 per cent of water for normal consistency.

In Series 138 the fresh-water normal consistency was 24.5 per cent; most of the impure waters in this series required a similar amount. Medicine Lake water (Sample 105) and acid waters from a spent plating bath of 10 and 20 per cent concentration required 25, 26, and 27 per cent, respectively.

Time of Setting.—In general, the time of setting of cements mixed with impure waters in a given series was about the same as for fresh water. None of the samples gave time of setting decidedly shorter than fresh waters. Sea water and synthetic sea water were somewhat more quick-setting in the Vicat test; the other tests were practically normal.

The following table shows the samples which gave abnormally long time of setting as compared with fresh waters:

Mixing Water	Sample No.	Time of Setting			
		Vicat Needle		Gillmore Needle	
		Initial	Final	Initial	Final
		h. m.	h. m.	h. m.	h. m.
SERIES 137					
Fresh		3 52	7 20	4 43	7 18
Great Salt Lake	5	6 45	11 15	7 30	11 15
10 per cent salt solution	9	4 25	9 30	5 45	9 45
15 per cent salt solution	10	5 00	9 30	6 30	9 45
20 per cent salt solution	11	6 00	10 30	9 30	.. ..
Refuse from oil refinery	40	11 00	36 00	9 00	48 00
SERIES 138					
Fresh	†	3 55	8 30	6 25	9 45
Industrial sewage	106	5 00	9 15	7 30	11 50
Corn products waste	111	5 30	9 20	7 50	11 15
Spent plating bath (10 per cent)	117	4 50	7 55	7 15	12 20
Spent plating bath (20 per cent)	117	5 45	11 15	8 05	13 00

* Average of 8 samples.
† Average of 3 samples.

Refuse from oil refinery (Sample 40) was very slow in setting (average 10 hr. initial and 42 hr. final). While the concrete tests at 3 and 7 days were somewhat erratic, the strength-ratios at ages of 28 days to 2 1/3 yr. ranged from 83 to 95 per cent, average 90 per cent, indicating that this water is satisfactory for mixing concrete.

The time of setting with Industrial Sewage water (106), Corn Products Waste (111) and acid waters from a spent plating bath (117) was somewhat longer than for the fresh waters, as shown by the above table.

The tests show that while the low-strength waters generally gave longer time of setting, there was no direct relation between time of setting and the strength-ratios of the different water samples. Time of setting is not a satisfactory criterion of suitability of a water for mixing concrete.

Soundness.—Soundness tests of the cement mixed with various waters were made in both series; in every case the cements passed the test satisfactorily.

Color and Odor of Waters.—Most of the waters in Series 137 were clear and colorless. The Minnesota bog waters had a yellow color due to decaying vegetation; water from a creek at Lakehurst Air Station, N. J. (Sample 38) and from the Monongahela River (39) were also yellow in color. Refuse from an oil refinery (40) was black and oily. "Bubbly Creek" water (44) was very dark in color.

The impure waters in Series 138 varied in color. Brewery waste (Sample 107), Drainage Canal water (108) Soap Works waste (109) and Corn Products waste (111) were light yellow in color. Gas plant waste (110) had a brown color and a turbid appearance, probably due to globules of oil in suspension. Tannery wastes were turbid; Soak water (114) and Lime soak (115) were white in color, probably due to lime in suspension. Lime soak contained some hair from hides. Paint manufacturing waste (116) was a deep red color and quite clear. Water from a spent plating bath (117) was dark brown and somewhat turbid. "Bubbly Creek" water (44 and 112) was very dark in color; a greasy scum collected on this water after standing for some time.

Few of the waters used had a pronounced odor. "Bubbly Creek" water gave off a very offensive odor; waste washings from beer storage vats (Sample 107) had a beer-like odor; a fresh water from the city water supply, Dundee, Mich., (18) and water from a creek at Lakehurst, N. J., (38) had an odor of hydrogen sulphide. Tannery wastes had a characteristic odor.

The tests show that neither color nor odor furnish a satisfactory criterion of the suitability of a water for mixing concrete.

Specifications for Quality of Mixing Water.—The following extracts from State Highway Specifications are typical of the requirements for quality of water for mixing concrete in road work:

(a) "All water used in concrete shall be subject to the approval of the Engineer and shall be reasonably clear, free from oil, acid, or vegetable substances and neither brackish nor salty." (Wis. and Utah.)

(b) "Water used for this work shall be reasonably clean, and free from oil, acid, alkali or vegetable substances." (Indiana.)

(c) "Water used for this work shall be reasonably clean, and free from oil, acid, alkali or vegetable substances. No salt or sea water shall be used in mixing any concrete." (California.)

(d) "The water shall be clean, free from oil, acid, alkali or vegetable substances, and the tensile strength of 1-3 mortars shall be equal to that developed with distilled water when mixed in the same proportion with the same cement and Ottawa sand." (Pennsylvania.)

(e) "Water used in concrete shall be free from sewage, oil, acid, strong alkalis or vegetable matter and also shall be free from clay and loam." (Ohio.)

(f) "Water used in concrete or in grout filler, shall be clean and free from oil, acid, alkali or vegetable matter. Before installing his water supply equipment, the contractor shall secure the Engineer's approval of the source of water supply which he proposes to use. If at any time the water from this source should become of unsatisfactory quality or insufficient quantity the Engineer may require the contractor to provide water from some other source." (Iowa and Minnesota.)

(g) "The water used in mixing portland cement concrete shall be clean, free from oil and organic matter, and when tested with litmus shall show no acid or alkaline reaction." (Illinois.)

(h) "Water shall be clean, free from oil, acid, alkali or vegetable matter." (Arizona and Colorado.)

(i) "Water shall be clean, free from oil, acid, alkali, vegetable matter, organic matter and other deleterious substances." (New York.)

(j) "All waters for use in concrete shall be clean, free from oil, acid, alkali, vegetable matter, sea salts, or ingredients that are injurious to concrete." (New Jersey.)

All the above specifications require that waters shall be *free from* impurities of various kinds. If these specifications were rigidly enforced, but few waters would be available for mixing concrete, as small quantities of impurities are found in practically all waters except rain and distilled waters.

The report of the Joint Committee on Standard Specifications for Concrete and Reinforced-concrete gives the following specifications for mixing water:

> "Water for concrete shall be clean and free from injurious amounts of oil, acid, alkali, organic matter or other deleterious substance."

This specification puts the emphasis on *injurious amounts* of impurities, but leaves open the methods of test.

Tests for Mixing Waters.—In only rare instances are definite tests specified for mixing waters. The U. S. Bureau of Public Roads recommends the following tests:

(1) Acidity and alkalinity, by use of blue and red litmus paper,
(2) Total solids and inorganic matter,
(3) Soundness, time of setting or mortar strength.

"Any indication of unsoundness, marked change in time of setting or a variation of more than 10 per cent in strength from results obtained with mixtures containing the water of satisfactory quality, shall be sufficient cause for rejection of the water under test."*

* Standard and Tentative Methods of Sampling and Testing Highway Materials, Bulletin 949, U. S. Dept. of Agriculture, 1921. A later edition, Bulletin 1216 (1924) requires the use of phenolphthalein or methyl orange as an indicator of acidity or alkalinity instead of litmus paper.

The litmus test is not of much value since it responds to minute quantities of acid or alkali which our tests have shown to be harmless in concrete. The test for total solids is likely to be misleading. Our studies did not reveal a single sample of impure mixing waters which caused unsoundness in the cement.

Concrete or mortar tests are the most satisfactory guides in important cases.

While this investigation did not cover all possible types of water, it seems safe to conclude that any water which is suitable for drinking or for ordinary household use can be accepted without question for mixing concrete. It has been found that many waters which are badly polluted with sewage and trade wastes are not injurious in concrete.

Effect of Sugar in Concrete.—One type of impurity which was not included in this series of tests, but which should be mentioned here, is sugar and related compounds such as alcohol and fruit juices. In general such compounds are fatal to concrete, since they practically destroy the hydraulic properties of the cement. Waters containing even small quantities of such materials should not be used either in mixing or curing concrete without thorough investigation.

RELATED TESTS.

This report includes only one phase of the general problem of the influence of impurities in concrete and does not touch upon the behavior of concrete when *exposed to* various types of waters and soils. Results have already been reported on previous tests on the effect of organic impurities in sands[1]. Exhaustive tests have been made in this Laboratory on the effect of powdered admixtures in concrete[2]. Field and laboratory tests are now under way on concrete exposed to sulphate soils and waters; including the effect of integral compounds. A summary of tests on the effect of integral water- and alkali-proofing compounds on the strength of concrete has been published[3]. A report has been prepared on the effect of calcium chloride and other soluble salts in concrete[4]. Tests are under way on the use of calcium chloride and similar materials as a curing agency for concrete.

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[1] Colorimetric Test for Organic Impurities in Sand, Circular 1, Structural Materials Research Lab., 1917. See also, Abrams-Harder Field Test for Organic Impurities in Sands; Report of Committee C-9, Proc. Am. Soc. Testing Materials, 1919.

[2] Effect of Hydrated Lime and other Powdered Admixtures in Concrete; Proc. Am. Soc. Testing Materials, 1920, Reprinted as Bulletin 8, Structural Materials Research Lab., Lewis Institute, Chicago.

[3] Effect of Integral Waterproofing Compounds on the Strength of Concrete; Industrial and Eng. Chemistry, May, 1923.

[4] Calcium Chloride as an Admixture in Concrete; Proc. Am. Soc. Testing Materials, 1920, Reprinted as Bulletin 13, Structural Materials Research Laboratory.

TABLE 1.—NOTES ON WATER SAMPLES—SERIES 137.

In general 5 to 10 gallons of each sample were secured for test.
See Table 2 for chemical analyses of water samples.

Sample	Origin of Water Samples
	GROUP 1.—FRESH WATERS.
2, 50	Lake Michigan; Chicago city water supply.
1, 49	Distilled water.
14	Coal City, Ill.; city water supply.
15	Tracy, Minn.; city water supply, from 700-ft. well.
17	Marshall, Minn.; city water supply from wells; high alkali content for potable water.
18	Dundee, Mich.; city water supply; has hydrogen sulfide odor; high alkali content for potable water.
36	Lake County, Ind.; rain water from small pools near Gary.
37	Youghiogheny River, foot of Fifth Street, McKeesport, Pa.
	GROUP 2.—MINNESOTA BOG WATERS.
19	Pale Face River } Fed by peat bogs or tamarack swamps; yellow color.
20	Helwig Creek } Probably average conditions for rivers in Northern Minnesota. Representative
21	Coloquet River } waters available for concrete work in St. Louis County.
24	Dunka River }
22	Stagnant pool in peat bag. Very little flow; peat floating on surface; yellow color.
23, 25	Sulphur Dam; typical of swamp waters in Northern Minnesota; yellow color.
	GROUP 3.—SEA WATER AND ALKALI WATERS.
3	Sea water from Atlantic Ocean, Wildwood, N. J.
16	Sea water from Atlantic Ocean, Bay Head, N. J. No sewage present.
4	Synthetic sea water; 3.5 per cent solution of salts approximating composition of sea water.
5	Great Salt Lake, Utah; contains about 20 per cent soluble salts and some vegetation.
26	Devil's Lake, N. D.; high in alkali.
27	Marshall, Minn. }
28	Roswell. N. M. } From low water flow of tile drains in alkali soils.
29	Montrose, Colo. }
31	Muddy Creek, Utah, 3 miles north of Emery; Federal Road Project; high alkali content.
46	Price, Utah; sample furnished by State Road Commission; alkaline.
	GROUP 4.—SOLUTIONS OF COMMON SALT.
6 to 11	Solutions of 1, 2, 5, 10, 15, and 20 per cent table salt in Lake Michigan water.
	GROUP 5.—MINE AND MINERAL WATERS.
12	Montrose, Colo.; mineral water from mineral spring at City Hall Square; highly carbonated.
30	Bisbee, Ariz.; Mine water.
32	Loop Creek, W. Va., Fayette Co.; 24 mines pump drainage into stream above this point.
33	Cambria, Ill.; coal mine water from mine pump discharge.
34	Colpville, Ill.; from mine pump discharge.
35	Fort Dodge, Iowa, Gypsum mine water, from mine pump discharge.
43	Scranton, Pa.; Coal washery waste, from mine pump discharge.
	GROUP 6.—WATERS CONTAINING SEWAGE AND INDUSTRIAL WASTE.
13	Illinois River, near Marseilles; carries sewage from Chicago Drainage Canal.
38	Lakehurst, N. J., Air Station; from creek; hydrogen sulfide odor; yellow color.
39	Monongahela River, below B. & O. Bridge at Wheeling Junction, Pa.; yellow color.
40	Franklin, Pa.; Refuse from oil refinery; black and oily.
42	Endicott, N. Y.; probably tannery waste.
44	"Bubbly Creek," Chicago; waste from Stock Yards; very dark color; scum on surface.
45	Cygnet, Ohio, from Rockford Creek; contains salt and oil scum from oil wells.
48	Allegheny River (low water) } From Franklin, Pa.; probably contains refuse from oil refineries.
41	Allegheny River (high water) }
47	Drainage Canal, Chicago; contains large quantity of sewage.

Table 2.—Chemical Analyses of Water Samples—Series 137.

Chemical analyses expressed as parts per million.
See Table 1 for further details of origin and nature of samples.

Sample	Source	Suspended Matter	Total Solids	Ignited Solids	Silica (SiO_2)	Iron and Aluminum Oxides (R_2O_3)	Calcium (Ca)	Magnesium (Mg)	Sodium and Potassium (Na & K)	Sulphate (SO_4)	Carbonate (CO_3)[a]	Chloride (Cl)
	Group 1.—Fresh Waters.											
2,50	Lake Michigan	..	150	150	..	..	35	25	..	15	70	5
1,49	Distilled water	..	...	...	..	..	..	..	..	..	...	...
14	City water, Coal City.	20	1,250	1,120	5	5	95	55	200	370	140	240
15	City water, Tracy	15	1,260	1,150	trace	trace	240	65	40	650	160	5
17	City water, Marshall..	low	2,770	2,600	..	..	340	100	400	1,480	210	65
18	City water, Dundee..	low	1,920	1,740	..	15	330	125	70	1,060	100	35
36	Lake County, Ind.	35	660	510	10	..	150	20	trace	170	140	25
37	Youghiogheny River.	low	25	15	5	5	1	1	0	0	trace	trace
	Group 2.—Minnesota Bog Waters.											
19	Pale Face River	low	115	80	15	5	15	5	5	10	30	5
20	Helwig Creek	70	115	80	5	5	15	5	5	10	..	..
31	Cloquet River	low	145	105	10	15	20	5	5	5	40	5
24	Dunka River	10	120	60	10	5	10	5	trace	10	20	5
22	Stagnant pool	low	195	130	5	10	25	10	trace	trace	70	5
23	Sulphur Dam	250	90	70	..	..	25	trace	..	15	20	10
25	Sulphur Dam	10	105	40	5	5	10	trace	5	..	10	5
	Group 3.—Alkali Waters.											
3	Sea water	100	33,400	33,420	..	..	350	1,000	11,100	2,370	30	18,500
16	Sea water	low	33,300	33,300	..	35	550	1,080	10,000	2,460	70	18,600
4	Synthetic sea water..	none	35,000	35,000	..	..	420	1,310	11,100	2,700	70	19,400[b]
5	Great Salt Lake	low	227,800	227,800	..	..	1,280	6,330	78,600	14,400	410	126,700
26	Devil's Lake, N. D...	15	4,000	4,000	15	5	20	trace	1,580	1,070	370	910
27	Tile Drain, Minn.	10	1,910	1,820	20	5	260	170	115	1,060	190	5
28	Tile Drain, N. M.	820	3,130	3,130	10	..	560	120	665	1,490	130	140
29	Tile Drain, Colo.	..	2,490	2,350	10	..	470	110	160	1,520	80	5
31	Muddy Creek, Utah..	240	12,100	12,100	..	2	5	270	3,320	7,700	210	220
46	Price, Utah	low	9,430	7,890	..	40	440	510	1,200	5,500	130	65
	Group 4.—Solutions of Common Salt.[c]											
6	1% common salt...	..	10,200	10,200	..	..	35	25	3,960	15	70	6,110
7	2% common salt...	..	20,400	20,400	..	..	35	25	7,980	15	70	12,300
8	5% common salt...	..	52,000	52,000	..	..	35	25	20,400	15	70	31,400
9	10% common salt...	..	107,500	107,500	..	..	35	25	42,200	15	70	65,100
10	15% common salt...	..	166,800	166,800	..	..	35	25	65,500	15	70	101,100
11	20% common salt...	..	223,100	223,100	..	..	35	25	87,800	15	70	135,200
	Group 5.—Mine and Mineral Waters.											
12	Mineral water, Colo..	..	2,140	2,060	5	trace	90	40	670	270	880	100
30	Mine water, Ariz.	25	400	360	5	trace	90	10	20	180	40	10
32	Loop Creek, W. Va..	low	720	680	15	5	70	40	80	450	10	10
33	Coal mine, Ill.	5	4,640	4,400	15	10	260	180	1,000	2,780	100	60
34	Coal mine, Ill.	15	2,240	2,120	trace	5	110	50	580	410	250	670
35	Gypsum mine, Iowa..	30	2,660	2,220	25	trace	560	80	80	1,370	90	10
43	Coal washery, Pa.	low	2,700	2,460	..	170	260	170	50	1,780	*d*	60
	Group 6.—Waters Containing Sewage and Industrial Wastes.											
13	Illinois River	low	970	920	5	trace	100	50	160	220	170	210
38	Lakehurst Air Station	10	450	390	15	50	40	10	10	250	5	5
39	Monongahela River..	40	300	270	5	15	30	10	50	150	..	5
40[e]	Refuse from oil refinery	..	...	...	..	..	...	...	...	...	..	...
42	Endicott, N. Y.	250	9,040	7,110	..	..	1,220	trace	1,650	1,000	470	2,200
44	"Bubbly Creek"	low	1,860	1,090	35	35	90	20	390	60	200	650
45	Cygnet, Ohio	low	4,300	4,020	..	20	290	130	1,190	250	50	2,180
48	Allegheny River (l.w.)	..	120	100	..	..	30	5	..	20	30	15
41	Allegheny River (h.w.)	..	250	220	5	5	30	60	10	30	70	30
47	Drainage Canal	low	260	220	15	20	40	10	10	50	80	trace

a Calculated from bicarbonates which were determined by titration.
b 65 parts per million of Bromine also present.
c Analyses calculated from analysis of Lake Michigan water and specific gravity of salt solutions.
d Water is acid; acidity equivalent to 3 parts of hydrogen per million parts of water.
e Qualitative only; acid reaction to methyl orange; high in chlorides, sulfates, calcium and magnesium; R_2O_3 present.

TABLE 3.—NOTES ON WATER SAMPLES—SERIES 138.

Water samples (except Samples 101-105) were collected in 50-gallon lots in the Chicago District. Chemical analyses given in Table 4.

Sample	Remarks
101	Lake Michigan; Chicago city water supply.
102	Distilled water.
103	Distilled water-aerated. (Air, filtered through cotton, was passed through water for several hours).
104	Synthetic sea water; 3.5 per cent solution of salts approximating composition of salts in sea water.
105	Medicine Lake, near Watertown, S. D.
106	Industrial sewage from Central Manufacturing District; collected at 39th and Morgan Sts.
107	Wash water from wood tanks used for beer storage; Atlas Brewing Co.
108	Chicago Drainage Canal at Ashland Ave. and 27th St.; contains sewage.
109	Waste water from Armour & Co., Soap Works, Chicago; contains some organic material
110	Circulating water used to seal water gas machines at North Station, Peoples Gas Co.
111	Waste from plant of Corn Products Refining Co., Argo, Ill.
112	"Bubbly Creek;" waste from Chicago Stock Yards; very dark color; scum on surface.
113	Tan and dye liquor waste; from tannery of Griess, Pfleger & Co.
114	Soak water; waste from cleaning hides; from tannery of Griess, Pfleger & Co.
115	Lime soak from tannery used in removing hair from hides; from Illinois Sanitary District Testing Station at tannery of Griess, Pfleger & Co.
116	Waste from settling tanks of Sherwin, Williams Co., paint manufacturers, Pullman, Ill.; contains sulphuric acid, organic matter, copper, and iron.
117	Spent acid plating bath, La Salle Steel Co., Cicero, Ill. Used in concrete diluted with 4 and 9 parts of water. Chemical analysis in Table 4 was made on the sample as received.

TABLE 4.—CHEMICAL ANALYSES OF WATER SAMPLES—SERIES 138.

Waters were from Chicago District, unless otherwise noted.
Analyses are expressed as parts per million of water as received.
See Table 3 for further details of origin and nature of samples

Mixing Water		Suspended Matter	Total Solids (105° C.)	Silica (SiO_2)	Iron and Aluminum Oxides (R_2O_3)	Calcium (Ca)	Magnesium (Mg)	Chloride (Cl)	Sulphate (SO_4)	Sulphide (S)	Oxygen to Oxidize Organic Matter
Sample	Source										
101	Lake Michigan	..	150	..	..	35	25	5	15	..	..
102	Distilled	..	...	..	..	..	..	...	...	..	..
103	Distilled aerated	..	...	..	..	...	...	...	...	..	..
104	Synthetic sea water[a]	..	35,000	..	..	420	1,310	19,400	2,700	..	..
105	Medicine Lake, S. D.[b]	55	53,100	..	..	420	5,750	540	28,700	..	..
106	Industrial sewage	10	310	10	5	50	180	45	0	0	5
107	Brewery waste	100	250	10	5	40	120	5	0	0	120
108	Drainage Canal	20	220	15	5	40	140	10	30	0	10
109	Soap works waste	20	410	5	5	60	190	90	60	0	15
110	Gas plant waste	120	470	30	5	40	240	170	150	35	420
111	Corn Products Co	170	980	15	5	90	370	330	120	5	75
112	Bubbly Creek	50	820	10	5	80	210	420	80	5	30
113	Tan and dye liquor (tannery)	110	1,840	25	5	70	150	480	560	20	310
114	Soak water (tannery)	90	3,700	20	5.	85	200	2,340	60	10	35
115	Lime soak (tannery)	970	6,220[c]	30	0	990	trace	2,910	210	320	320
116	Paint manufacturing waste[d]	110	10,180	10	30	180	70	130	5,430	0	440
117	Spent plating bath[e]	90	...	..	..	0	0	810	114,400	..	..

[a] Sodium and potassium 78,600 parts per million; carbonate (CO_3) 70.
[b] Loss on ignition 8,610 parts per million; sodium (Na) 2820; potassium (K) 700; carbonate (CO_3) 430.
[c] Total solids after ignition.
[d] Loss on ignition 895 parts per million; copper, 170; zinc, trace.
[e] Ferrous iron 47,300, acidity (H_2SO_4) 31,250 parts per million. Diluted to 10 and 20 per cent of original concentration by the addition of Lake Michigan water before using in the tests.

TABLE 5.—CHEMICAL ANALYSIS OF CEMENTS.

The percentages are the average of 2 determinations.

Cement	Used in Series	Silica (SiO_2)	Iron and Aluminum Oxides ($Fe_2O_3 + Al_2O_3$)	Calcium Oxide (CaO)	Magnesium Oxide (MgO)	Sulfuric Anhydride (SO_3)
4951	137	21.88	9.46	62.64	2.94	1.55
5075	137	21.73	9.15	62.90	2.79	1.62
5259	138	21.85	9.25	61.97	2.78	1.68

TABLE 6.—MORTAR TESTS OF CEMENTS.

1:3 standard sand mortar.
Portland cements a mixture of equal parts of 5 brands purchased in Chicago.
Mixing water from Chicago city water supply.
Tests made in accordance with Standard Specifications and Tests for Portland Cement of the American Society for Testing Materials.
Each value for strength is the average of 5 tests made on different days.
Time of setting tests given in Tables 8 and 9.

Cement	Used in Series	Fineness Residue on 200 Sieve	Normal Consistency	Tensile Strength of Briquets, lb. per sq. in.						Compression Tests of 2x4-in. Cylinders lb. per sq. in.					
				7 days	28 days	3 mo.	6 mo.	1 year	2 years	7 days	28 days	3 mo.	6 mo.	1 year	2 years
4951	137	18.2	22.5	270	360	425	390	400	375	2220	3740	4340	4840	4260	4800
5075	137	18.8	22.5	250	350	420	445	340	380	1710	3010	4020	3640	4030	3630
5259	138	18.2	24.0	255	375	410	...	415	395*	1700	2800	3550	....	3730	3840*

* Age of test, 2⅛ years.

TABLE 7.—SIEVE ANALYSIS OF AGGREGATES.

Sieve analyses made using square mesh wire cloth manufactured by The W. S. Tyler Co., Cleveland.
Aggregate: Sand and pebbles from Elgin, Ill.; largely limestone origin. Sand contained 2 per cent silt, mostly clay.

Series	Kind of Aggregate	Amounts Coarser than Each Sieve, per cent by weight									Fineness Modulus*	Unit Weight, lb. per cu. ft.
		No. 100	No. 48	No. 28	No. 14	No. 8	No. 4	⅜ in.	¾ in.	1½ in.		
137	Sand	99	88	55	38	20	0	..	..	..	3.00	112
	Pebbles	100	100	100	100	100	100	67	0	..	6.67	110
	Mixed concrete aggregate	99	94	79	71	63	55	39	0	..	5.00	126
138	Sand	98	87	58	38	16	3	0	..	..	3.00	112
	Pebbles	100	100	100	100	100	100	75	25	0	7.00	110
	Mixed concrete aggregate	99	96	86	79	72	68	50	17	0	5.67	128

* Fineness modulus of aggregate is the sum of the percentages in the sieve analysis, divided by 100.

TABLE 8.—TIME OF SETTING OF CEMENT AS AFFECTED BY IMPURE WATERS—SERIES 137.

Portland Cement consisted of a mixture of equal parts of 5 brands purchased in Chicago. (Cement 4,951, see Table 6.)

Tests were made in accordance with Standard Specifications and Tests for Portland Cement of the American Society for Testing Materials.

Each value is the average of 2 tests made on different days.

Group	Classification	Sample	Source of Mixing Water	Normal Consistency	Vicat Needle		Gillmore Needle		Soundness (over boiling water)
					Initial	Final	Initial	Final	
					h. m.	h. m.	h. m.	h. m.	
		2,50	Lake Michigan	22.5	3 25	6 30	4 30	6 30	OK
		1,49	Distilled water	22.5	3 40	7 00	4 30	7 00	OK
		14	City water, Coal City, Ill.	22.5	3 40	6 30	4 30	6 30	OK
		15	City water, Tracy, Minn.	23.0	4 00	8 00	4 30	8 00	OK
1	Fresh waters	17	City water, Marshall, Minn.	22.5	4 00	6 20	5 00	7 10	OK
		18	City water, Dundee, Mich.	22.5	3 40	6 50	5 00	7 25	OK
		36	Lake County, Ind.	22.5	4 30	7 30	4 30	7 30	OK
		37	Youghiogheny River	22.5	4 00	8 00	5 15	8 15	OK
			Average		3 52	7 20	4 43	7 18	
		19	Pale Face River	22.5	3 45	6 30	5 00	7 15	OK
		20	Helwig Creek	22.5	3 30	6 30	4 45	7 15	OK
		21	Cloquet River	22.5	3 50	6 40	5 00	7 00	OK
2	Minnesota bog waters	24	Dunka River	23.0	3 45	8 00	4 45	8 00	OK
		22	Stagnant pool	22.5	3 30	6 45	4 30	7 10	OK
		23	Sulphur Dam	22.5	3 30	7 00	4 30	7 30	OK
		25	Sulphur Dam	22.5	3 30	6 10	4 30	6 45	OK
			Average		3 37	6 48	4 43	7 16	
		3	Sea water	22.5	3 45	7 15	4 30	7 45	OK
		16	Sea water	22.5	2 45	6 00	4 00	6 30	OK
		4	Synthetic sea water	22.5	3 30	7 00	4 35	7 00	OK
		5	Great Salt Lake	24.0	5 45*	11 15*	7 30*	11 15*	OK
3	Sea water and alkali waters	26	Devil's Lake N. D.	23.0	3 30	7 00	4 45	7 00	OK
		27	Tile Drain, Minn.	22.5	3 30	7 00	5 00	7 00	OK
		28	Tile Drain, N. M.	22.5	3 15	6 00	4 30	6 50	OK
		29	Tile Drain, Colo.	22.5	4 00	6 15	4 40	6 45	OK
		31	Muddy Creek, Utah	23.0	3 15	8 00	4 45	8 00	OK
		36	Price, Utah	23.0	3 15	7 00	4 20	7 30	OK
			Average		3 25	6 50	4 36	7 10	
		6	1 per cent common salt	22.5	3 30	7 00	4 35	7 15	OK
		7	2 per cent common salt	22.5	3 30	7 30	4 45	7 30	OK
4	Solutions of common salt	8	5 per cent common salt	23.0	3 45	7 30	4 45	7 30	OK
		9	10 per cent common salt	24.0	4 25	9 30	5 45	9 45	OK
		10	15 per cent common salt	24.5	5 00	9 30	6 30	9 45	OK
		11	20 per cent common salt	25.0	6 00	10 30	9 30	.....	
			Average		4 22	8 35	5 58	8 21	
		12	Mineral water, Colo.	23.0	3 30	6 55	5 00	7 00	OK
		30	Mine water, Ariz.	23.0	4 00	6 25	5 00	6 50	OK
5	Mine and mineral waters	32	Loop Creek, W. Va.	22.5	3 45	7 45	4 45	7 45	OK
		33	Coal mine, Ill.	23.0	3 45	7 45	4 40	7 50	OK
		34	Coal mine, Ill.	23.5	3 45	8 00	5 00	8 15	OK
		35	Gypsum mine, Ia.	23.0	3 45	8 00	5 00	8 15	OK
		43	Coal washery, Pa.	23.0	4 00	7 30	4 45	8 00	OK
			Average		3 47	7 29	4 53	7 42	
		13	Illinois River	23.0	4 00	6 50	5 00	7 15	OK
		38	Lakehurst Air Station	22.5	4 00	7 30	4 30	7 45	OK
		39	Monongahela River	22.5	3 45	7 30	4 30	8 00	OK
6	Waters containing industrial wastes and sewage	40	Refuse, Oil Refinery	26.0	11 00*	36 00*	9 00*	48 00*	OK
		42	Endicott, N. Y. (tannery)	22.0	3 30	7 45	4 50	8 00	OK
		44	"Bubbly Creek," Chicago	22.5	4 00	7 30	4 45	7 50	OK
		45	Cygnet, Ohio	23.0	3 15	7 00	4 20	7 45	OK
		47	Drainage Canal, Chicago	22.5	3 35	7 15	4 45	8 00	OK
		48	Allegheny River (low water)	22.5	3 45	7 15	4 40	7 45	OK
		41	Allegheny River (high water)	22.5	3 45	7 45	4 45	7 45	OK
			Average		3 44	7 22	4 41	7 47	

* Omitted from average.

TABLE 9.—TIME OF SETTING OF CEMENT—SERIES 138.

Cement: a mixture of 5 brands of Portland Cement purchased in Chicago, see Tables 5 and 6 for chemical analysis and physical tests.

Tests made in accordance with Standard Specifications and Tests for Portland Cement of the American Society for Testing Materials.

Each value is the average of 2 tests made on different days.

Mixing Water		Normal Consistency	Time of Setting				Soundness (over boiling water)
			Vicat Needle		Gillmore Needle		
Sample	Source		Initial	Final	Initial	Final	
			h. m.	h. m.	h. m.	h. m.	
101	Lake Michigan	24.0	4 25	8 40	6 40	10 35	OK
102	Distilled	23.5	3 30	8 10	6 10	9 20	OK
103	Distilled aerated	24.0	3 45	8 45	6 25	9 20	OK
	Average	24.0	3 55	8 30	6 25	9 45	
104	Synthetic sea water	24.0	2 30	6 20	5 15	8 25	OK
105	Medicine Lake, S. D.	25.0	4 20	9 00	6 40	10 50	OK
106	Industrial sewage	24.0	5 00	9 15	7 30	11 50	OK
107	Brewery waste	23.5	4 00	8 50	6 30	10 30	OK
108	Drainage Canal	24.0	4 30	9 00	6 40	10 30	OK
109	Soap works waste	24.0	4 20	8 40	7 10	10 55	OK
110	Gas plant waste	24.0	5 05	9 05	7 00	10 50	OK
111	Corn Products Co.	24.5	5 30	9 20	7 50	11 15	OK
112	"Bubbly Creek"	24.0	4 25	8 50	7 10	10 35	OK
113	Tan and dye liquor (tannery)	24.0	4 50	8 50	7 10	10 30	OK
114	Soak water	24.0	3 50	8 40	6 20	10 40	OK
115	Lime soak (tannery)	23.5	4 00	8 00	7 15	11 10	OK
116	Paint manufacturing waste	23.5	3 30	8 10	6 35	10 50	OK
117 (10)*	Spent plating bath	26.0	4 50	7 55	7 15	12 20	OK
117 (20)*	Spent plating bath	27.0	5 45	11 15	8 05	13 00	OK

* Percentage of Sample 117 mixed with Lake Michigan water.

TABLE 10.—COMPRESSION TESTS OF CONCRETE USING IMPURE MIXING WATERS—SERIES 137.

4 by 8-in. concrete cylinders.
Mix 1–4 by volume.
Relative consistency 1.10; water-ratio 0.88; plasticity measured by means of flow table.
Aggregate: sand and pebbles from Elgin, Ill., graded 0-¾-in.
Each value is the average of 5 or 6 tests made on different days.
The values in parentheses are "Strength Ratios," that is percentages of the average strength in Group 1 or a given age and curing condition.
See Figs. 1 to 3.

Sample	Source of Mixing Water	Flow	Compressive Strength, lb. per sq. in.								
			Cured in Moist Room Until Test						Cured in Moist Room 28 Days, Remainder in Air		
			3 days	7 days	28 days	3 mo.	1 year	2⅓ years	3 mo.	1 year	2⅓ years
	GROUP 1.—FRESH WATERS										
2	Lake Michigan	212	960 (100)	1510 (94)	3160 (102)	4610 (106)	5650 (104)	5770 (112)	4730 (109)	4060 (104)	3620 (108)
50	Lake Michigan	229	870 (91)	1430 (89)	3120 (101)	4000 (92)	5320 (98)	5750 (112)	4130 (95)	3970 (102)	2670 (80)
1	Distilled water	214	900 (94)	1630 (102)	3020 (98)	4560 (105)	5430 (100)	5250 (102)	4330 (99)	3750 (96)	3390 (102)
49	Distilled water	218	950 (99)	1560 (98)	2780 (90)	3480 (80)	5390 (99)	3540 (69)	4400 (101)	3430 (88)	3320 (99)
14	City water, Coal City, Ill.	216	990 (103)	1560 (98)	2870 (93)	4150 (96)	5140 (94)	5070 (99)	3800 (87)	3980 (102)	2790 (84)
15	Tracy, Minn.	224	900 (94)	1550 (97)	2760 (90)	4160 (96)	5360 (98)	4770 (93)	4120 (95)	3790 (97)	3400 (102)
17	Marshall, Minn.	216	1020 (106)	1760 (110)	3140 (102)	4730 (109)	5740 (105)	5740 (112)	4540 (104)	3960 (102)	3710 (111)
18	Dundee, Mich.	214	1040 (108)	1700 (106)	3140 (102)	4690 (108)	5440 (100)	5640 (110)	4780 (110)	3940 (101)	3600 (108)
36	Lake County, Ind.	214	990 (103)	1620 (101)	3450 (112)	4610 (106)	5480 (101)	4340 (85)	4580 (105)	4120 (106)	3380 (101)
37	Youghiogheny River	214	930 (97)	1650 (103)	3400 (110)	4390 (101)	5540 (102)	5390 (105)	4100 (94)	3960 (102)	3540 (106)
	Average	216	960 (100)	1600 (100)	3080 (100)	4340 (100)	5450 (100)	5130 (100)	4350 (100)	3900 (100)	3340 (100)
	GROUP 2.—MINNESOTA BOG WATERS										
19	Pale Face River	220	830 (86)	1720 (107)	3410 (111)	4860 (112)	5980 (110)	5000 (98)	4380 (101)	4290 (110)	3070 (92)
20	Helwig Creek	217	830 (86)	1740 (108)	3070 (100)	4390 (101)	5430 (100)	4220 (82)	..	..	..
21	Cloquet River	217	960 (100)	1780 (111)	2750 (89)	4160 (96)	4920 (90)	4700 (92)	..	..	..
24	Dunka River	221	930 (97)	1750 (109)	3130 (102)	..	..	..	..	..	..
22	Stagnant pool	218	1000 (104)	1680 (105)	3410 (111)	4350 (98)	5100 (94)	5390 (105)	..	..	..
23	Sulphur Dam	220	1080 (112)	1850 (116)	3280 (106)	4180 (96)	5870 (108)	4350 (85)	..	..	..
25	Sulphur Dam	217	880 (92)	1550 (97)	2970 (96)	4710 (109)	5540 (102)	5840 (114)	..	..	..
	Average	219	930 (97)	1720 (107)	3150 (102)	4440 (102)	5470 (100)	4920 (96)			

TABLE 10.—COMPRESSION TESTS OF CONCRETE USING IMPURE MIXING WATERS—SERIES 137 (*continued*).

Sample	Source of Mixing Water	Flow	Compressive Strength, lb. per sq. in.								
			Cured in Moist Room Until Test						Cured in Moist Room 28 Days, Remainder in Air		
			3 days	7 days	28 days	3 mo.	1 year	2½ years	3 mo.	1 year	2½ years
	GROUP 3.—SEA WATER AND ALKALI WATERS										
3	Sea water	209	1200 (125)	1700 (106)	2790 (90)	3470 (80)	4840 (89)	4230 (82)	4030 (93)	3880 (99)	3460 (104)
16	Sea water	220	1180 (123)	1840 (115)	2650 (86)	3490 (81)	4600 (84)	4510 (88)	3600 (83)	3910 (100)	2980 (89)
4	Synthetic sea water	214	1320 (137)	1490 (93)	2610 (85)	3640 (84)	4520 (83)	4520 (88)	3740 (86)	3750 (96)	3660 (110)
5	Great Salt Lake	200	1080 (112)	1460 (91)	2380 (77)	3300 (76)	3870 (71)	3360 (65)	3800 (87)	4090 (105)	3260 (98)
26	Devil's Lake, N. D.	221	980 (102)	1730 (107)	3050 (99)	4180 (96)	5360 (98)	4620 (90)	4140 (95)	3560 (91)	3340 (100)
27	Tile drain, Minn.	216	1020 (106)	1720 (107)	3310 (108)	4650 (107)	5680 (104)	4690 (91)	4350 (100)	4240 (109)	3970 (119)
28	Tile drain, N. Mex.	210	1210 (126)	1800 (112)	3160 (102)	4170 (96)	5420 (100)	5070 (99)	4620 (106)	3780 (97)	3590 (107)
29	Tile drain, Colo.	213	1030 (107)	1730 (107)	3180 (103)	4340 (100)	5710 (105)	4910 (96)	4320 (99)	3910 (100)	3320 (99)
31	Muddy Creek, Utah	219	1180 (123)	1480 (93)	2790 (90)	3880 (89)	5340 (98)	5010 (98)	4540 (104)	3660 (94)	3390 (102)
46	Price, Utah	233	1090 (113)	1490 (93)	2820 (91)	4190 (97)	4990 (92)	4450 (87)	4290 (99)	3500 (90)	3110 (93)
	Average	216	1130 (118)	1640 (102)	2870 (92)	3930 (91)	5030 (92)	4540 (88)	4140 (95)	3830 (98)	3410 (102)
	GROUP 4.—SOLUTIONS OF COMMON SALT										
6	1 per cent common salt	212	1070 (111)	1680 (105)	2600 (84)	3720 (86)	4710 (86)	4490 (87)	4030 (93)	3420 (88)	3700 (111)
7	2 per cent common salt	221	1210 (126)	1640 (102)	2710 (88)	3830 (88)	4660 (86)	4840 (94)	3640 (84)	3630 (93)	3240 (97)
8	5 per cent common salt	234	1120 (117)	1450 (90)	2310 (75)	2900 (67)	3940 (72)	4050 (79)	3360 (77)	3690 (95)	3670 (110)
9	10 per cent common salt	238	1030 (107)	1400 (87)	2100 (68)	2750 (63)	3650 (67)	3050 (59)	2850 (66)	3520 (90)	3250 (97)
10	15 per cent common salt	240	850 (89)	1200 (75)	2020 (65)	2840 (65)	3080 (57)	2880 (56)	276 (63)	3640 (93)	3640 (109)
11	20 per cent common salt	238	740 (77)	1130 (70)	1870 (61)	2660 (61)	3210 (59)	3150 (61)	2950 (68)	3450 (88)	3960 (119)
	Average	230	1000 (104)	1420 (89)	2270 (73)	3120 (72)	3880 (71)	3740 (73)	3260 (75)	3560 (91)	3530 (106)

TABLE 10.—COMPRESSION TESTS OF CONCRETE USING IMPURE MIXING WATERS—SERIES 137 (*continued*).

Sample	Source of Mixing Water	Flow	Compressive Strength, lb. per sq. in.								
			Cured in Moist Room Until Test						Cured in Moist Room 28 Days, Remainder in Air		
			3 days	7 days	28 days	3 mo.	1 year	2⅓ years	3 mo.	1 year	2⅓ years
	GROUP 5.—MINE AND MINERAL WATERS										
12	Mineral water, Colo.	220	1020 (106)	1600 (100)	2360 (77)	3590 (83)	4650 (85)	4780 (93)	3710 (85)	3240 (83)	2660 (80)
30	Mine waters, Ariz.	219	870 (91)	1610 (101)	3090 (100)	..	..	..	..	..	..
32	Loop Creek, W. Va.	213	960 (100)	1670 (104)	3150 (102)	4440 (102)	5480 (101)	4500 (88)	4260 (98)	3810 (98)	3420 (102)
33	Coal mine, Ill.	219	1010 (105)	1630 (102)	3150 (102)	4020 (93)	5580 (102)	5260 (103)	4420 (102)	3630 (93)	3660 (110)
34	Coal mine, Ill.	215	1110 (116)	1660 (104)	3140 (102)	4420 (102)	5450 (100)	4080 (80)	4310 (99)	3390 (87)	3800 (114)
35	Gypsum mine, Ia.	222	1050 (109)	1700 (106)	3050 (99)	4560 (105)	5660 (104)	4690 (91)	4760 (110)	4040 (104)	3280 (98)
43	Coal washery, Pa.	230	1010 (105)	1600 (100)	2990 (97)	4470 (103)	5640 (104)	4780 (93)	3790 (87)	3720 (95)	3490 (105)
	Average.	220	1000 (104)	1640 (102)	2990 (97)	4250 (98)	5410 (100)	4680 (91)	4210 (97)	3640 (93)	3390 (102)
	GROUP 6.—WATERS CONTAINING INDUSTRIAL WASTE AND SEWAGE										
13	Illinois River.	224	970 (101)	1490 (93)	2570 (83)	3690 (85)	4920 (90)	4650 (91)	3990 (92)	3590 (92)	3390 (102)
38	Lakehurst Air Station.	214	880 (92)	1570 (98)	3050 (99)	4420 (102)	5560 (102)	4060 (79)	4440 (101)	3870 (99)	2960 (89)
39	Monongahela River.	217	940 (98)	1530 (96)	3070 (100)	4280 (99)	5360 (98)	4540 (88)	..	..	..
40	Refuse, oil refinery.	182	630 (66)	1840 (115)	2890 (94)	3820 (88)	4510 (83)	4880 (95)	..	..	..
42	Endicott, N. Y. (tannery)	226	950 (99)	1370 (86)	2510 (81)	3740 (86)	4590 (84)	4190 (82)	3410 (78)	3480 (89)	2790 (84)
44	"Bubbly Creek," Chicago	226	1090 (114)	1540 (96)	2950 (96)	4330 (100)	5500 (101)	4790 (94)	4400 (101)	3540 (91)	3360 (100)
45	Cygnet, Ohio.	224	1100 (115)	1820 (114)	2660 (86)	3890 (90)	4960 (91)	3950 (77)	4250 (98)	3790 (97)	2930 (88)
47	Drainage Canal.	217	990 (103)	1540 (96)	3000 (97)	4210 (97)	5120 (94)	4810 (94)	4570 (105)	3740 (96)	3910 (117)
48	Allegheny River (low water).	219	940 (88)	1660 (104)	3030 (98)	4560 (105)	5660 (104)	4850 (95)	4290 (99)	4040 (104)	3500 (105)
41	Allegheny River (high water).	222	900 (94)	1500 (94)	3000 (97)	4350 (100)	5730 (105)	3820 (74)	..	..	..
	Average.	217	940 (98)	1590 (99)	2870 (93)	4130 (95)	5190 (95)	4450 (87)	4190 (96)	3730 (95)	3260 (98)

The strength-ratios are from the curves for moist-room curing in Fig. 2.

Five per cent of common salt lowers the freezing point of water about 6° F., but *reduces the strength* of the concrete nearly 30 per cent. Due to the serious reduction of strength by solutions of common salt, their use in mixing water should not be permitted.

Mine and Mineral Waters.—7 samples of water were collected from mines in Arizona, Illinois, Iowa, Pennsylvania, West Virginia and from a mineral spring in Colorado. Chemical analyses of these waters showed them to contain solids ranging from 400 to 4640 parts per million. It is interesting to note that pumpage waters from coal and gypsum mines made good concrete. The only water in this group which gave abnormal values was Sample 12, from a mineral spring in Montrose, Colo. This water was highly carbonated when discharged. Its strength-ratios were 106, 100, 77, 83, 85 and 93 per cent. The other waters gave approximately normal strengths.

A mine water (Sample 30) from Bisbee, Arizona, and Sample 32 from Loop Creek, W. Va., which receives pumpage from 24 coal mines, showed a lower proportion of impurities than some of the fresh waters from city water supplies and for this reason might have been included with the fresh waters. Whether these samples are so included makes little difference since their strength ratios were practically 100 per cent.

Sewage and Industrial Wastes.—The waters in Group 6, Series 137, have been classified under this heading, as well as most of the waters in Series 138. These waters may be divided into those containing sanitary sewage and miscellaneous industrial wastes. The waters containing sanitary sewage are discussed below under: Chicago Drainage Canal, Illinois River Water and Monongahela River Water. Undoubtedly many of the waters listed under Industrial Wastes contained sanitary sewage, but they are primarily carriers of wastes from manufacturing plants.

Chicago Drainage Canal carries Chicago's sewage, diluted with flow from Lake Michigan. This water (Samples 47 and 108) was tested in both Series. The chemical analyses showed both samples to be low in solids. In both series of tests this water gave concrete strengths about the same as the fresh waters.

Illinois River Water (Sample 13) was collected near Marseilles. In spite of the fact that this stream carried Chicago's sewage, the chemical analysis shows comparatively little foreign matter; the total solids were less than for many of the fresh waters. The concrete tests using this water gave results not materially different from the fresh waters; while strength-ratios as low as 83 per cent were obtained at 28 days, it is probable that these variations were more or less accidental, since the ratios increased at 2 1/3 yr. to 91 and 102 per cent for moist room and air curing. Strength-ratios for waters from the Chicago Drainage Canal and Illinois River are summarized in Table 17.

Monongahela River Water (Sample 39) was comparatively free from foreign material and gave strengths approximately normal.

Allegheny River Water (Samples 41 and 48) gave strengths approximately normal. There was no essential difference in the results obtained from the low water and high water samples.

Industrial Wastes.—Waters carrying concentrated wastes from many different industries were tested in both Series. The tests are discussed under:

Refuse from oil refinery,
Tannery wastes,
Waters from "Bubbly Creek", Chicago,
Brewery waste,
Soap works waste,
Gas plant waste,
Waste from Corn Products Refining Co.,
Paint factory waste,
Acid waters,
Miscellaneous wastes.

Refuse from Oil Refinery from Franklin, Pa., (Sample 40) contained large quantities of chlorides, sulphates, calcium and magnesium. The strength-ratios were 66, 115, 94, 88, 83 and 95 per cent. The low value at 3 days is explained by the extremely slow setting of the cement; Table 8 shows that initial setting was delayed to about 10 hr. and final setting to over 36 hr. Normal consistency of the cement with this sample was 26 per cent as compared with 22.5 per cent for fresh waters.

Tannery Wastes.—Three samples of waste from a tannery in Chicago were tested in Series 138; Sample 42 in Series 137 from Endicott, N. Y., probably contained tannery wastes. The principal impurities appear to be calcium chloride and small quantities of sulphates. The strength-ratios for these samples are summarized in Table 18. Tan and dye liquor (Sample 113) gave strength-ratios of from 96 per cent to 99 per cent for concrete mixtures of 1: 7 to 1: 2 at 28 days. For relative consistencies of 0.90 to 1.50 in a 1: 4 mix at 28 days this sample gave strength-ratios ranging from 88 to 99 per cent. In 1: 4 concrete (relative consistency 1.00) at ages of 3 days to 2 1/3 yr., the strength-ratios were in no cases less than 94 per cent.

Soak Water (Sample 114) gave strength-ratios for the different conditions of test ranging from 86 per cent to 114 per cent, average 94 per cent.

Lime Soak (Sample 115) gave consistently lower strength-ratios than Samples 113 and 114. For this water the strength-ratios ranged from 78 to 100 per cent and were generally less than 85 per cent. The strength-ratios for *Tannery Waste* (Sample 42) were essentially the same as for Sample 115.

"Bubbly Creek" water (Samples 44 and 112) contains waste from the Chicago Stockyards and "Packingtown" and probably represents the most polluted body of water in the world. The odor is extremely offensive. During the summer a scum consisting of grease and other materials forms on the surface. Concrete tests were made using this water in both series. The strength-ratios are summarized in Table 19 and are plotted in Fig.

TABLE 11.—TESTS OF CONCRETE OF DIFFERENT MIXTURES—SERIES 138.

Compression tests of 6 x 12-in. concrete cylinders.
Mix by volume; relative consistency 1.00.
Aggregate: Sand and pebbles from Elgin, Ill., graded 0 to 1½ in.
Age at test, 28 days.
Each value is the average of 10 tests made on different days unless otherwise noted.
Values for compressive strength expressed in pounds per square inch.
The values in parentheses are "Strength Ratios," that is, percentages of the average strength for fresh waters.
See Fig. 4.

Sample	Mixing Water: Source	1:7[a] (1.03) Flow	1:7[a] (1.03) Compressive Str.	1:5 (0.85) Flow	1:5 (0.85) Compressive Str.	1:4[b] (0.75) Flow	1:4[b] (0.75) Compressive Str.	1:3 (0.65) Flow	1:3 (0.65) Compressive Str.	1:2 (0.55) Flow	1:2 (0.55) Compressive Str.	Average (0.77) Flow	Average (0.77) Compressive Str.
101	Lake Michigan	151	1880	178	3010	181	3670	187	4480	187	5350	177	3680
102	Distilled	144	1890	158	3080	171	3680	176	4440	174	5060	163	3630
103	Distilled aerated	142	1900	156	3070	178	3700	173	4600	171	5100	162	3670
	Average	146	1890 (100)	164	3050 (100)	177	3680 (100)	179	4510 (100)	177	5170 (100)	167	3660 (100)
104	Synthetic sea water	145	1840 (97)	155	2820 (93)	177	3290 (89)	171	3980 (88)	173	4670 (90)	162	3310 (91)
106	Industrial sewage	154	1850 (98)	168	3150 (103)	184	3780 (103)	169	4480 (99)	182	5220 (101)	171	3680 (100)
107	Brewery waste	157	1980 (106)	178	3120 (102)	194	3800 (104)	180	4500 (100)	196	5230 (101)	181	3730 (102)
108	Drainage Canal	154	2150 (114)	179	3230 (106)	191	3870 (105)	190	4390 (97)	194	5300 (102)	180	3790 (103)
109	Soap works waste	162	1980 (105)	176	3110 (102)	193	3770 (103)	190	4400 (98)	190	5210 (101)	181	3690 (101)
110	Gas plant waste	159	1870 (99)	177	3050 (100)	195	3630 (99)	186	4290 (95)	197	4880 (94)	182	3540 (97)
111	Corn Products Co.	156	1840 (97)	163	3050 (100)	184	3460 (94)	184	4240 (94)	179	4930 (95)	171	3500 (96)
112	"Bubbly Creek," Chicago	150	1980 (105)	176	3030 (99)	192	3720 (101)	181	4370 (97)	191	5050 (97)	177	3630 (99)
113	Tan and dye liquor (tannery)	152	1880 (99)	172	2990 (98)	185	3630 (99)	189	4440 (98)	189	4950 (96)	176	3680 (98)
114	Soak water (tannery)	157	1840 (97)	170	2870 (94)	187	3480 (94)	187	4160 (92)	184	4860 (94)	177	3440 (94)
115	Lime soak (tannery)	178	1580 (83)	200	2450 (80)	211	3130 (85)	212	3720 (82)	203	4160 (80)	201	3010 (82)
116	Paint manufacturing waste	158	1660 (88)	167	2730 (89)	190	3210 (87)	190	3580 (79)	187	4620 (89)	177	3160 (86)
117 (10) [c]	Spent plating bath	139	2270 (120)	131	3330 (109)	148	3500 (95)	141	4170 (93)	145	4600 (89)	139	3570 (98)
117 (20) [c]	Spent plating bath	139	2040 (108)	124	3020 (99)	136	3250 (88)	149	3770 (83)	153	4350 (84)	140	3290 (90)
	Average of impure waters	154	1910 (101)	168	2990 (98)	183	3540 (96)	180	4170 (92)	183	4870 (95)	172	3490 (95)

[a] The first value is the mixture in terms of volume of cement and aggregate; the values in parentheses are the "water-ratios" of the concrete.
[b] Values are average of 30 tests from 3 groups; same values are given in Tables 12 and 13.
[c] Percentage of Sample 117 used with Lake Michigan water.

TABLE 12.—TESTS OF CONCRETE OF DIFFERENT CONSISTENCIES—SERIES 138.

Compression tests of 6 x 12-in. cylinders.
Mix 1:4 by volume.
Aggregate: Sand and pebbles from Elgin, Ill., graded 0 to 1½ in.
Age at test, 28 days.
Each value is the average of 10 tests made on different days unless otherwise noted.
The values for strength are expressed in pounds per square inch.
The values in parentheses are "Strength Ratios," that is, percentages of the average strength for fresh waters.
See Fig. 5.

Mixing Water		0.90[a] 0.68		10.0[b] 0.75		1.10 0.82		1.25 0.92		1.50 1.09		Average 0.85	
Sample	Source	Flow	Compressive Str.	Flow	Compressive Str.	Flow	Compressive Str.	Flow	Compressive Str.	Flow	Compressive Str.	Flow [c]	Compressive Str.
101	Lake Michigan	130	4300	181	3670	215	3350	[d]	2850	[d]	1540	172	3140
102	Distilled	131	4170	171	3680	219	3270	...	2470	...	1620	177	3040
103	Distilled aerated	135	4140	178	3700	216	3420	...	2430	...	1600	177	3060
	Average	132	4200 (100)	177	3680 (100)	217	3350 (100)	...	2580 (100)	...	1590 (100)	174	3080 (100)
104	Synthetic sea water	136	3660 (87)	177	3290 (89)	205	2830 (85)	...	2240 (87)	...	1470 (92)	174	2690 (87)
106	Industrial sewage	136	4110 (98)	184	3780 (103)	233	3230 (96)	...	2450 (95)	...	1580 (100)	183	3030 (98)
107	Brewery waste	142	4250 (101)	194	3800 (104)	234	3360 (100)	...	2570 (100)	...	1580 (100)	190	3110 (101)
108	Drainage Canal	144	4380 (104)	191	3870 (105)	219	3470 (104)	...	2670 (104)	...	1530 (96)	184	3180 (103)
109	Soap works waste	141	4230 (101)	193	3770 (103)	206	3330 (99)	...	2500 (97)	...	1550 (97)	180	3080 (100)
110	Gas plant waste	141	4000 (95)	195	3630 (99)	226	3210 (96)	...	2380 (92)	...	1520 (96)	183	2950 (96)
111	Corn Products Co.	136	3830 (91)	184	3460 (94)	226	3200 (96)	...	2510 (97)	...	1480 (93)	182	2900 (94)
112	"Bubbly Creek," Chicago	141	4000 (95)	192	3720 (101)	228	3300 (99)	...	2500 (97)	...	1580 (100)	187	3020 (98)
113	Tan and dye liquor (tannery)	133	4060 (97)	185	3630 (99)	220	3100 (93)	...	2260 (88)	...	1500 (94)	178	2910 (95)
114	Soak water (tannery)	137	3890 (93)	187	3480 (94)	225	3900 (92)	...	2390 (93)	...	1370 (86)	183	2840 (92)
115	Lime soak (tannery)	158	3500 (83)	211	3130 (85)	243	2640 (79)	...	2030 (79)	...	1260 (79)	202	2510 (82)
116	Paint manufacturing waste	141	3740 (89)	190	3210 (87)	233	2850 (85)	...	2150 (83)	...	1340 (84)	188	2660 (86)
117 (10) [e]	Spent plating bath	118	3790 (90)	148	3500 (95)	169	3140 (94)	...	2510 (97)	...	1680 (106)	143	2920 (95)
117 (20) [e]	Spent plating bath	115	3910 (93)	136	3250 (88)	162	3160 (94)	...	2500 (97)	...	1650 (104)	136	2890 (94)
	Average of impure waters	137	3950 (94)	183	3540 (96)	216	3130 (93)	...	2400 (93)	...	1570 (99)	178	2900 (94)

[a] The first figure represents the "relative consistency" of the concrete; the second figure is the "water-ratio."
[b] Values are average of 30 tests from 3 groups. Same values are given in Tables 11 and 13.
[c] Flows average of relative consistencies, 0.90, 1.00, and 1.10 only.
[d] Over limit of flow table.
[e] Percentage of Sample 117 used with Lake Michigan water.

TABLE 13.—TESTS OF CONCRETE AT DIFFERENT AGES—SERIES 138.

Compression tests of 6 x 12-in. concrete cylinders.
Mix 1:4 by volume.
Relative consistency 1.00; water-ratio *a* 0.75.
Aggregate sand and pebbles from Elgin, Ill., graded 0 to 1½-in.
Values for compressive strength expressed in pounds per square inch.
Each value is the average of 10 tests made on different days unless otherwise noted.
The values in parenthesis are "Strength Ratios," that is, percentages of the average strength for fresh waters.
See Fig. 6.

Mixing Water		Flow	Compressive Strength, lb. per sq. in.					
Sample	Source		3 days	7 days	28 days *b*	3 months	1 year	2½ years
101	Lake Michigan	181	1240	2150	3670	5350	6140	6200
102	Distilled water	171	1270	2240	3680	5340	6060	6680
103	Aerated distilled	178	1170	1990	3700	5140	5810	6500
	Average	177	1230 (100)	2130 (100)	3680 (100)	5280 (100)	6000 (100)	6460 (100)
104	Synthetic sea water	177	1590 (129)	2250 (106)	3290 (89)	4200 (79)	5260 (88)	5380 (81)
105	Medicine Lake, S. D.	141	1350 (110)	2170 (102)	3220 (88)	4430 (84)	5270 (88)	5950 (92)
106	Industrial sewage	184	1230 (100)	2090 (98)	3780 (103)	5220 (99)	5910 (99)	6420 (99)
107	Brewery waste	194	1190 (97)	2080 (98)	3800 (104)	5290 (100)	5710 (95)	6060 (94)
108	Drainage Canal	191	1240 (101)	2170 (102)	3870 (105)	5200 (98)	6070 (101)	6480 (100)
109	Soap works waste	193	1260 (102)	2100 (99)	3770 (103)	5090 (96)	5910 (99)	6660 (103)
110	Gas plant waste	195	1160 (94)	2000 (94)	3630 (99)	4860 (92)	5470 (91)	6260 (97)
111	Corn Products Co.	184	1220 (99)	2020 (95)	3460 (94)	4790 (90)	5460 (91)	6070 (94)
112	"Bubbly Creek," Chicago	192	1300 (106)	2130 (100)	3720 (101)	5160 (98)	5880 (98)	6340 (98)
113	Tan and dye liquor (tannery)	185	1300 (106)	2070 (97)	3630 (99)	4960 (94)	5650 (94)	6270 (97)
114	Soak water (tannery)	187	1400 (114)	2150 (101)	3480 (94)	4730 (90)	5350 (89)	6090 (94)
115	Lime soak (tannery)	211	1230 (100)	1870 (88)	3130 (85)	4120 (78)	4900 (82)	5660 (88)
116	Paint manufacturing waste	190	1110 (90)	1740 (82)	3210 (87)	4200 (80)	5210 (87)	5720 (88)
117 (10) *c*	Spent plating bath	148	1050 (85)	1880 (88)	3500 (95)	4580 (87)	5280 (88)	5610 (87)
117 (20) *c*	Spent plating bath	136	910 (74)	1840 (86)	3250 (88)	4630 (88)	5340 (89)	5580 (85)
	Average of impure waters	181	1230 (100)	2040 (96)	3510 (95)	4760 (90)	5500 (92)	6040 (93)

a 10 per cent more mixing water was used for Sample 117 (20), due to quick stiffening.
b Values are average of 30 tests made from three groups. Same values are given in Tables 11 and 12.
c Percentage of Sample 117 used with Lake Michigan water.

TABLE 14.—TESTS OF 1:3 STANDARD SAND MORTARS—SERIES 138.

Compression tests of 2 x 4-in mortar cylinders and tension tests of briquets.
Tests made in accordance with Standard Specifications and Tests for Portland Cement of the American Society for Testing Materials.
Specimens stored in water until test; tested damp.
Each value is the average of 5 tests made on different days.
The values in parentheses are "Strength Ratios," that is percentages of the average strength for fresh waters.

Sample	Mixing Water: Source	Flow	Water, per cent by weight	Tensile Strength, lb. per sq. in. (Briquets): 3 days	7 days	28 days	3 mo.	1 year	2½ years	Compressive Strength, lb. per sq. in. (2 by 4-in. Cylinders): 3 days	7 days	28 days	3 mo.	1 year	2½ years
101	Lake Michigan	112	10.5	215	255	375	410	415	395	1060	1700	2800	3550	3730	3840
102	Distilled water	114	10.5	220	290	400	380	420	390	1170	1810	2920	3760	4130	4140
103	Distilled aerated	112	10.5	235	260	400	400	430	395	1190	1520	2630	3840	4370	3680
	Average	113	10.5	220 (100)	270 (100)	390 (100)	395 (100)	420 (100)	395 (100)	1140 (100)	1680 (100)	2780 (100)	3720 (100)	4080 (100)	3890 (100)
104	Synthetic sea water	115	10.5	225 (102)	280 (104)	370 (95)	370 (94)	400 (95)	400 (101)	1320 (116)	1740 (104)	2660 (96)	3470 (93)	3680 (90)	3510 (90)
105	Medicine Lake, S. D.	110	10.7	230 (105)	300 (111)	415 (106)	425 (108)	420 (100)	395 (100)	1300 (114)	1870 (111)	2730 (98)	3680 (99)	3930 (96)	3990 (103)
106	Industrial sewage	114	10.5	225 (102)	285 (106)	375 (96)	390 (99)	400 (95)	395 (100)	1100 (96)	1550 (92)	2810 (101)	3640 (98)	4310 (106)	3320 (85)
107	Brewery waste	113	10.5	220 (100)	290 (107)	360 (92)	390 (99)	390 (93)	395 (100)	1180 (104)	1750 (104)	2800 (101)	3950 (106)	4440 (109)	3900 (100)
108	Drainage Canal	112	10.5	210 (95)	270 (100)	365 (94)	390 (99)	390 (93)	370 (94)	1080 (95)	1650 (98)	2700 (97)	3740 (101)	4290 (105)	3480 (90)
109	Soap works waste	116	10.5	210 (95)	265 (98)	370 (95)	410 (104)	430 (102)	365 (92)	1070 (94)	1660 (99)	2810 (101)	3530 (95)	3980 (97)	3870 (99)
110	Gas plant waste	114	10.5	210 (95)	280 (104)	365 (94)	400 (101)	385 (92)	370 (94)	1040 (91)	1760 (105)	2720 (98)	3680 (99)	4090 (100)	3620 (93)
111	Corn Products Co.	115	10.5	210 (95)	275 (102)	360 (92)	410 (104)	365 (87)	385 (97)	1190 (104)	1820 (108)	2650 (96)	3760 (101)	4060 (99)	3180 (82)
112	"Bubbly Creek," Chicago	114	10.5	200 (91)	265 (98)	350 (90)	420 (106)	385 (92)	375 (95)	1110 (97)	1640 (98)	2710 (97)	3580 (96)	3980 (97)	3820 (98)
113	Tan and dye liquor (tannery)	116	10.5	225 (102)	280 (104)	380 (97)	420 (106)	420 (99)	365 (92)	1130 (99)	1800 (107)	2550 (92)	3380 (91)	3540 (86)	3770 (97)
114	Soak water (tannery)	112	10.5	225 (102)	285 (106)	345 (88)	400 (101)	405 (96)	385 (97)	1230 (108)	1860 (111)	2710 (97)	3130 (84)	3570 (87)	3790 (97)
115	Lime soak (tannery)	135	10.5	210 (95)	265 (98)	320 (82)	340 (86)	355 (85)	385 (97)	1140 (100)	1760 (105)	2380 (86)	3210 (86)	3530 (86)	3140 (81)
116	Paint manufacturing waste	114	10.5	220 (100)	270 (100)	365 (94)	350 (89)	400 (95)	405 (102)	1190 (104)	1780 (106)	2890 (104)	3550 (95)	3970 (97)	3570 (92)
117 (20)[a]	Spent plating bath	106	11.0	180 (82)	270 (100)	370 (95)	440 (111)	420 (100)	365 (92)	1270 (111)	1830 (109)	3030 (109)	3870 (104)	4460 (109)	4380 (113)
117 (10)[a]	Spent plating bath	111	10.8	210 (95)	285 (106)	410 (105)	430 (109)	435 (104)	385 (97)	1250 (110)	1880 (112)	2720 (98)	3960 (106)	4420 (108)	4220 (109)
	Average of impure waters	114	10.5	215 (98)	260 (104)	365 (94)	400 (101)	396 (94)	380 (96)	1170 (103)	1760 (105)	2720 (98)	3600 (97)	4020 (99)	3710 (95)

[a] Percentage of Sample 117 used with Lake Michigan water.

TABLE 15.—SUMMARY OF TESTS OF CONCRETE MIXED WITH FRESH WATER.

Mix, 1:4 by volume. See Tables 10 and 13 and Figs. 3 and 6.
For data on other mixes and consistencies using fresh water see Tables 11 and 12.

Curing Condition	Compressive Strength, lb. per sq. in.					
	3 days	7 days	28 days	3 months	1 year	2½ years
Series 137—Relative Consistency 1.10						
Moist room	960	1600	3080	4340	5450	5130
Moist room 28 days, remainder in air	....	....	....	4350	3900	3340
Series 138—Relative Consistency 1.00						
Moist room	1230	2130	3680	5280	6000	6460

TABLE 16.—STRENGTH-RATIOS OF CONCRETE MIXED WITH SEA WATER AND SYNTHETIC SEA WATER.

Mix 1:4 by volume, unless otherwise noted.
Relative consistency 1.10 for Series 137 and 1.00 for Series 138, unlese otherwise noted.
For details, see Tables 10 to 13; also Figs. 4 to 6.

Sea Water			Synthetic Sea Water								
Samples 3 and 16 Series 137			Sample 4—Series 137			Sample 104—Series 138					
						Moist Room Curing					
Age at Test	Moist Room	Air*	Age at Test	Moist Room	Air*	Age at Test	Strength Ratio	Mix by Volume	Strength Ratio	Relative Consistency	Strength Ratio
3 days	124	..	3 days	137	..	3 days	129	1:7	97	0.90	87
7 days	110	..	7 days	93	..	7 days	106	1:5	93	1.00	89
28 days	88	..	28 days	85	..	28 days	89	1:4	89	1.10	85
3 months	80	88	3 months	84	86	3 months	79	1:3	88	1.25	87
1 year	86	100	1 year	83	96	1 year	88	1:2	90	1.50	92
2½ years	85	96	2½ years	88	110	2½ years	81				

* Moist room 28 days; remainder in air.

TABLE 17.—STRENGTH-RATIOS FOR CONCRETE MIXED WITH WATER FROM CHICAGO DRAINAGE CANAL AND ILLINOIS RIVER.

Mix 1:4, by volume.
Series 137 was begun Aug., 1920; Series 138, April, 1921.
For details see Table 10; also Fig. 6.

Age at Test	Strength-Ratio, per cent				
	Illinois River		Chicago Drainage Canal		
	Sample 13 Series 137		Sample 47 Series 137		Sample 108 Series 138
	Moist Room	Air	Moist Room	Air	Moist Room
3 days	101	..	103	..	101
7 days	93	..	96	..	102
28 days	83	..	97	..	105
3 months	85	92	97	105	98
1 year	90	92	94	96	101
2⅓ years	91	102	94	117	100

TABLE 18.—STRENGTH-RATIOS OF CONCRETE MIXED WITH TANNERY WASTES.

For details see Tables 10 to 13, also Fig. 4 to 6.

Mix	Relative Consistency	Water-Cement Ratio	Age at Test	Strength-Ratio, per cent			
				Series 137	Series 138		
				Tannery Waste (42)	Tan and Dye Liquor (113)	Soak Water (114)	Lime Soak (115)
1:7	1.00	1.03	28 days	..	99	97	83
1:5	1.00	0.85	28 days	..	98	94	80
1:4	1.00	0.75	28 days	..	99	94	85
1:3	1.00	0.65	28 days	..	98	92	82
1:2	1.00	0.55	28 days	..	96	94	80
1:4	0.90	0.68	28 days	..	97	93	83
1:4	1.00	0.75	28 days	..	99	94	85
1:4	1.10	0.82	28 days	..	93	92	79
1:4	1.25	0.92	28 days	..	88	93	79
1:4	1.50	1.09	28 days	..	94	86	79
1:4	1.00	....	3 days	99*	106	114	100
1:4	1.00	....	7 days	86*	97	101	88
1:4	1.00	....	28 days	81*	99	94	85
1:4	1.00	....	3 months	86*	94	90	78
1:4	1.00	....	1 year	84*	94	89	82
1:4	1.00	....	2⅓ years	82*	97	94	88

* Relative consistency 1.10; see Table 10.

TABLE 19.—STRENGTH-RATIOS OF CONCRETE MIXED WITH WATER FROM "BUBBLY CREEK".

Mix 1:4; age at test, 28 days, unless otherwise noted.
Moist-room curing, unless otherwise noted.
For details see Tables 10 to 13, also Fig. 4 to 6.

Sample 44—Series 137			Sample 112—Series 138					
Age at Test	Strength-Ratio, per cent		Age at Test	Strength-Ratio, per cent	Mix	Strength-Ratio, per cent	Relative Consistency	Strength-Ratio, per cent
	Moist Room	Air						
3 days.....	114	..	3 days	106	1:7	105	0.90	95
7 days.....	96	..	7 days	100	1:5	99	1.00	101
28 days.....	96	..	28 days	101	1:4	101	1.10	99
3 months....	100	101	3 months	98	1:3	97	1.25	97
1 year.....	101	91	1 year	98	1:2	97	1.50	100
2⅓ years....	94	100	2⅓ years	98				

TABLE 20.—STRENGTH-RATIOS OF CONCRETE MIXED WITH WASTES FROM CORN PRODUCTS PLANT AND PAINT FACTORY

Mix 1:4; relative consistency 1.00; age at test, 28 days, unless otherwise noted.
See Tables 11 to 13 for details; also Fig. 4 to 6.

Water Sample	Mix	Strength-Ratio, per cent	Relative Consistency	Strength-Ratio, per cent	Age at Test	Strength-Ratio, per cent
Corn Products (111).....	1:7	97	0.90	91	3 days	99
	1:5	100	1.00	94	7 days	95
	1:4	94	1.10	96	28 days	94
	1:3	94	1.25	97	3 months	90
	1:2	95	1.50	93	1 year	91
					2⅓ years	94
Paint Factory (116).....	1:7	88	0.90	89	3 days	90
	1:5	89	1.00	87	7 days	82
	1:4	87	1.10	85	28 days	87
	1:3	79	1.25	83	3 months	80
	1:2	89	1.50	84	1 year	87
					2⅓ years	88

TABLE 21.—STRENGTH-RATIOS OF CONCRETE MIXED WITH ACID WATERS.

Sample 117, Series 138. See Tables 11 to 13 for details; also Fig. 4 to 6.
Mix 1:4; relative consistency 1.00; age at test, 28 days, unless otherwise noted.
10 and 20 per cent refer to quantity of acid water mixed with water from Lake Michigan.

Mix	Strength-Ratio per cent		Relative Consistency	Strength-Ratio per cent		Age at Test	Strength-Ratio per cent	
	10	20		10	20		10	20
1:7	120	108	0.90	90	93	3 days	85	74
1:5	109	99	1.00	95	88	7 days	88	86
1:4	95	88	1.10	94	94	28 days	95	88
1:3	93	83	1.25	97	97	3 months	87	88
1:2	89	84	1.50	106	104	1 year	88	89
						2⅓ years	87	85

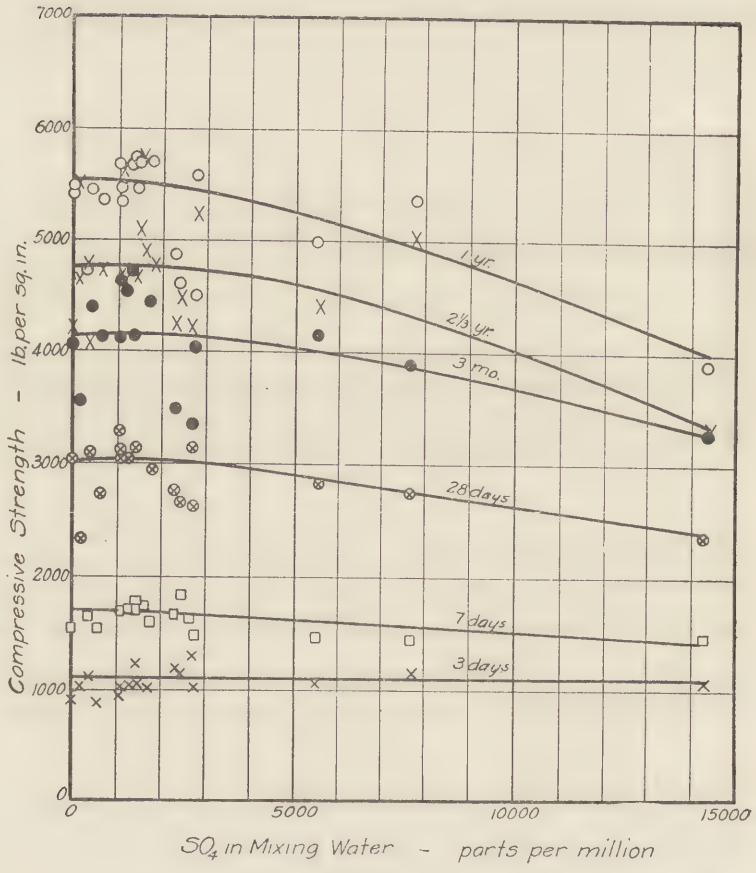


FIG. 1.—EFFECT OF SO_4 IN MIXING WATER ON THE STRENGTH OF CONCRETE.

(Data from Series 137.)

Compression tests of 4 x 8-in. concrete cylinders, cured in moist room. Mix 1 : 4 by volume; relative consistency 1.10; aggregate graded 0-¾-in. Cement: a mixture of 5 brands of portland cement purchased in Chicago. Each value is the average of 5 or 6 tests made on different days.

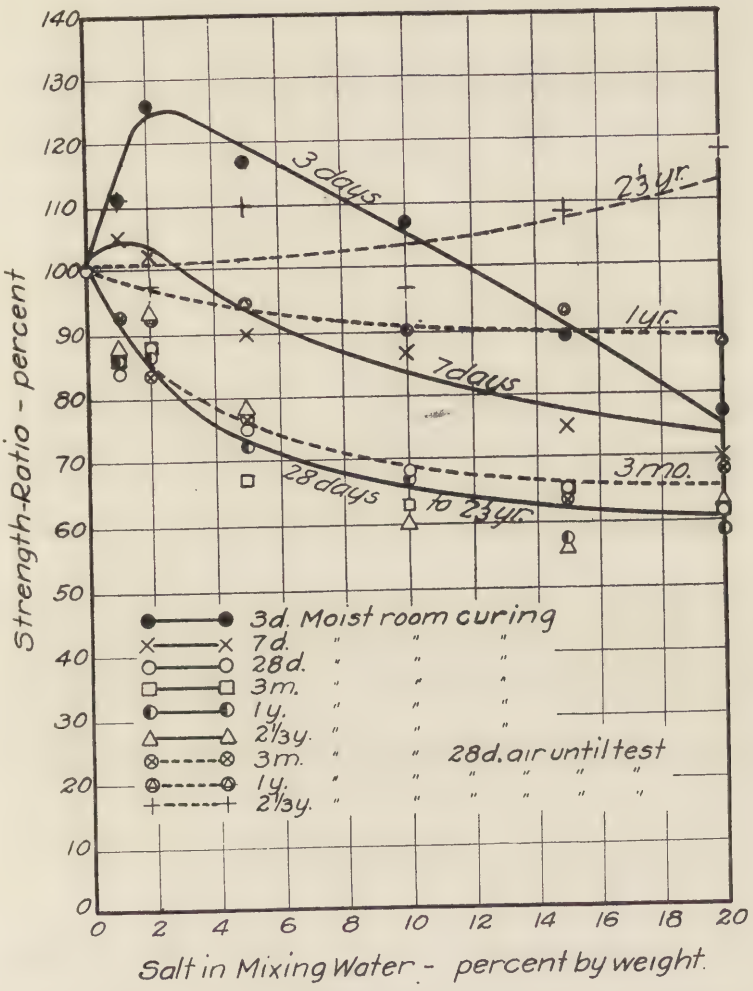


FIG. 2.—EFFECT OF COMMON SALT IN MIXING WATER ON THE STRENGTH OF CONCRETE.

(Data from Series 137.)

Compression tests of 4 x 8-in. concrete cylinders. Mix 1 : 4 by volume; relative consistency 1.10; aggregate graded 0-¾-in. Each value is the average of 5 or 6 tests made on different days.

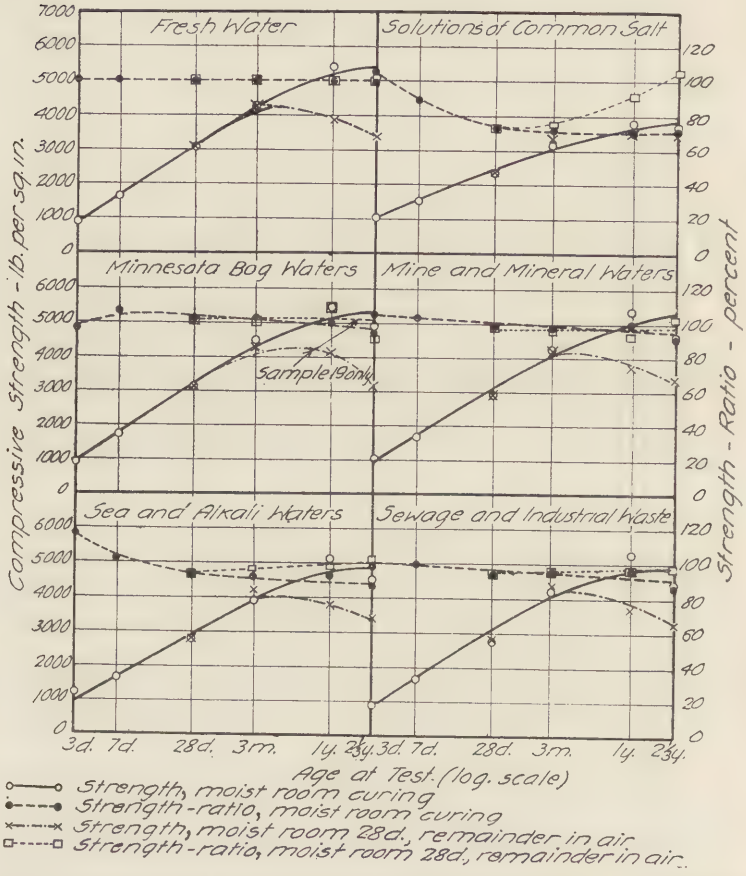


FIG. 3.—EFFECT OF TYPE OF MIXING WATER ON THE STRENGTH OF CONCRETE.

(Data from Series 137.)

Compression tests of 4 x 8-in. concrete cylinders. Mix 1 : 4 by volume; relative consistency 1.10; aggregate graded 0-¾-in. Each value is the average for all of the waters in a given group.

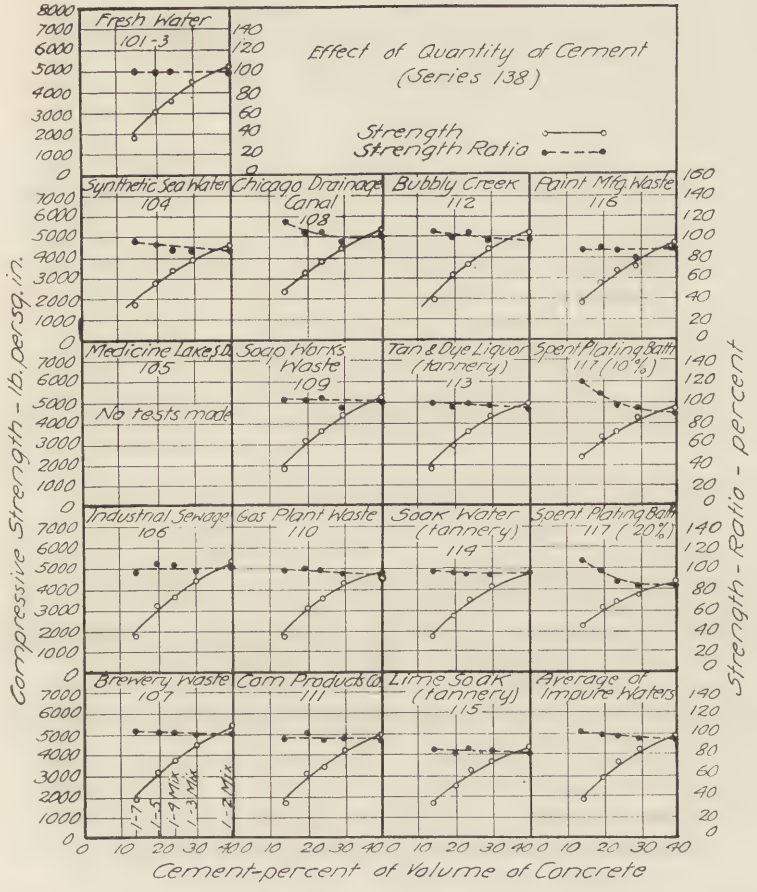


FIG. 4.—EFFECT OF QUANTITY OF CEMENT ON THE STRENGTH OF CONCRETE MIXED WITH IMPURE WATERS.

(Data from Series 138.)

Compression tests of 6 x 12-in. concrete cylinders, cured in moist room. Mix by volume; relative consistency 1.00; aggregate graded 0-1½ in. Cement: a mixture of 5 brands of portland cement purchased in Chicago. Age at test 28 days. In general, each value is the average of 10 tests made on different days.

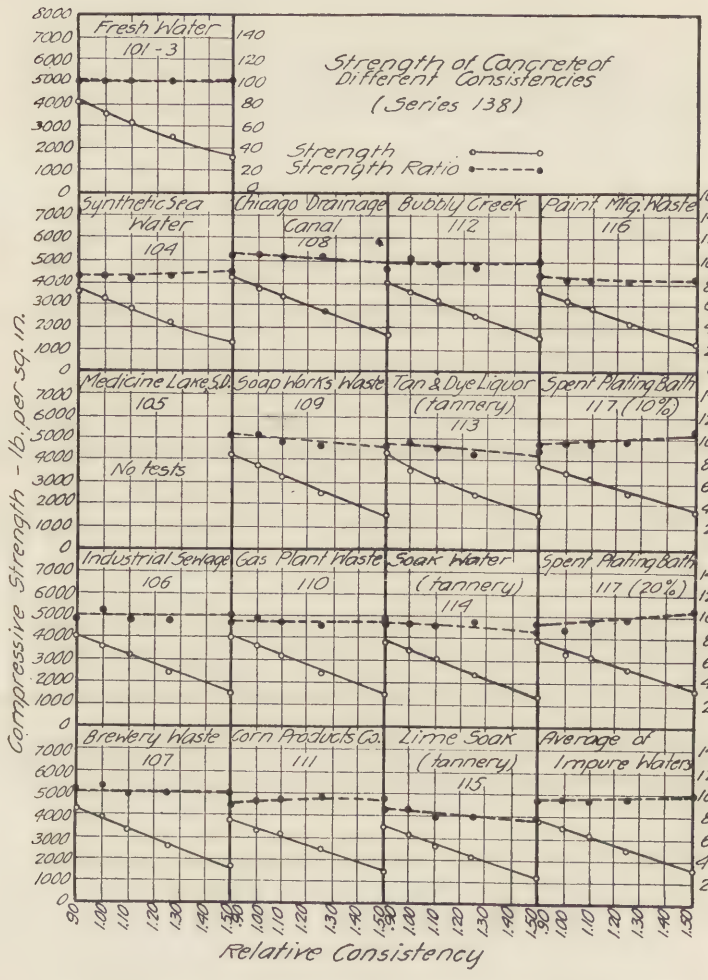


FIG. 5.—EFFECT OF CONSISTENCY ON THE STRENGTH OF CONCRETE MIXED WITH IMPURE WATERS.

(Data from Series 138.)

Compression tests of 6 x 12-in. concrete cylinders, cured in moist room. Mix 1 : 4 by volume; aggregate graded 0-1½ in. Age at test 28 days. In general, each value is the average of 10 tests made on different days.

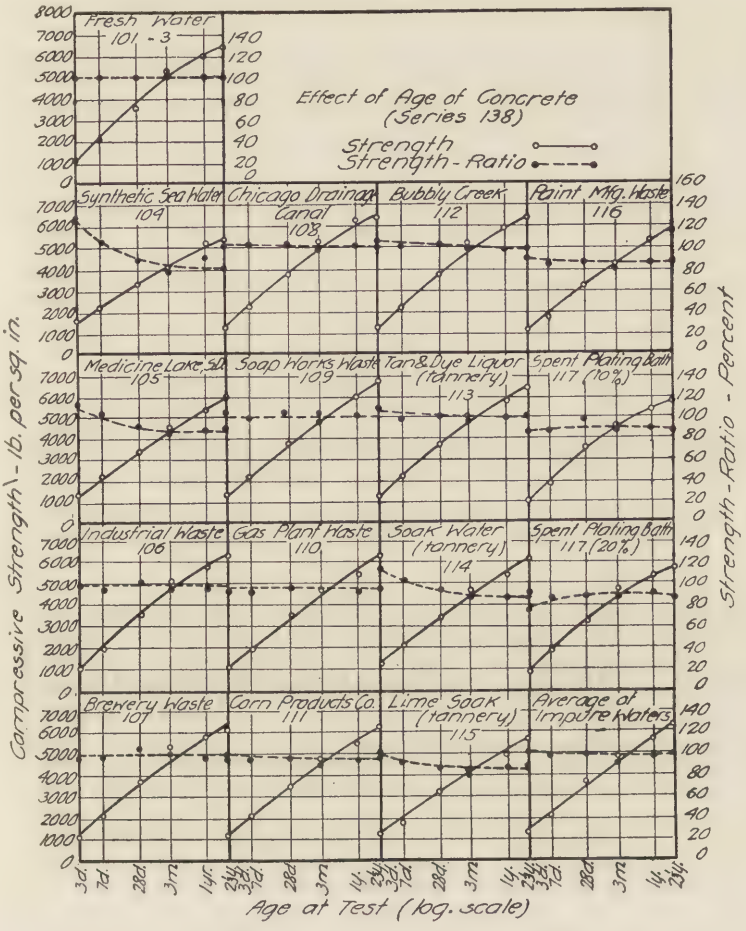


FIG. 6.—EFFECT OF AGE ON THE STRENGTH OF CONCRETE MIXED WITH IMPURE WATERS.

(Data from Series 138.)

Compression tests of 6 x 12-in. concrete cylinders, cured in moist room. Mix 1 : 4 by volume; relative consistency 1.00; aggregate graded 0-1½ in. In general, each value is the average of 10 tests made on different days.

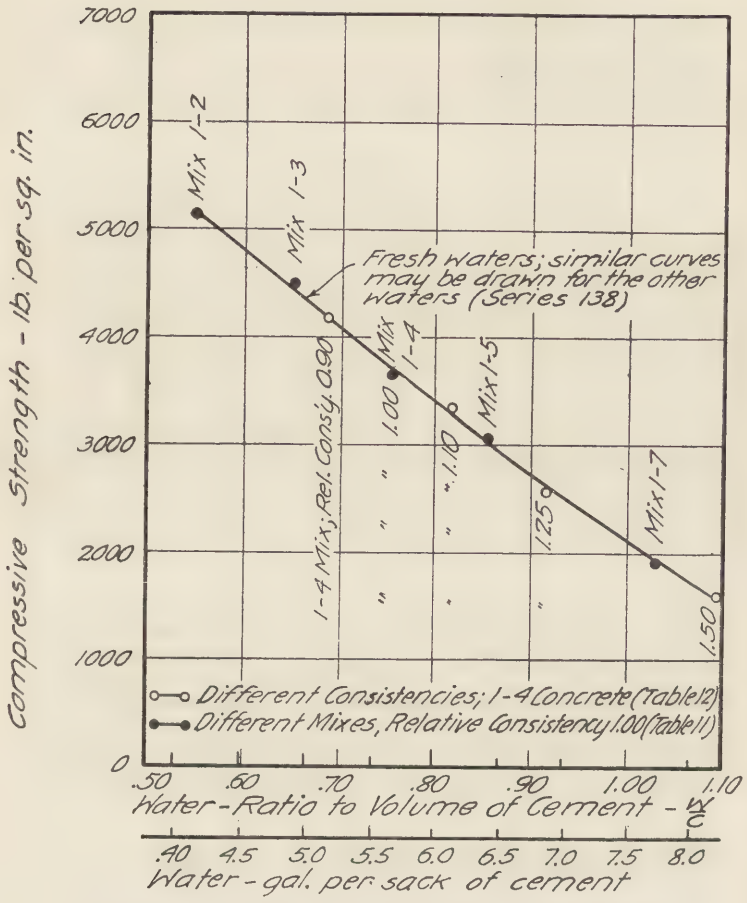


FIG. 7.—EFFECT OF QUANTITY OF MIXING WATER ON THE STRENGTH OF CONCRETE.

(Data from Series 138.)

Compression tests of 6 x 12-in. concrete cylinders, cured in moist room. Mix by volume; aggregate graded 0-1½ in. Age at test 28 days. In general, each value is the average of 30 tests.

Bulletin 13

Structural Materials Research Laboratory
Lewis Institute
Chicago

Calcium Chloride as an Admixture in Concrete

By

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FOREWORD

This paper was originally published in the Copyrighted Proceedings of the American Society for Testing Materials, Vol. 24, Part II, 1924. The discussions which appear in the Proceedings have been omitted.

Acknowledgment is made to the Society for permission to reprint the paper in bulletin form.

CALCIUM CHLORIDE AS AN ADMIXTURE IN CONCRETE

By Duff A. Abrams[1]

SUMMARY AND CONCLUSIONS

Calcium chloride and other soluble compounds of calcium-chloride base have been recommended as "accelerators" or admixtures in concrete for attaining rapid set and early strength. These investigations, which were originally begun in cooperation with Committee C-9 of the American Society for Testing Materials, were made to study the effect of such admixtures on the compressive strength of concrete and mortar. Strength tests of concrete and mortar were made at ages of 2 days to 3 years using admixtures of calcium chloride from two different manufacturers and three proprietary compounds of calcium-chloride base. The tests covered a wide range of mixtures, consistencies, and curing conditions, and included studies with four different brands of cement. In one series of tests, magnesium chloride was included. For purpose of comparison parallel tests were made on concrete and mortar without admixtures. A few tests were made using calcium chloride in concrete cured at low temperature.

Tests were made on about 7500 compression specimens in three separate investigations as follows:

Series 156.—Compression tests of concrete and mortar at ages of 2 days to 3 years using two different brands of calcium chloride, standard and low chlorine "Cal," Vitriflux, and magnesium chloride in varying amounts of admixtures. Tests on one brand of calcium chloride were extended to include a wide range of mixes, consistencies, curing conditions and four different portland cements.

Series 158.—Compression tests of 1:5.2 concrete at ages of 7 days to $2\frac{1}{2}$ years using calcium chloride as admixture for a wide range of periods of curing in moist room followed by air curing. The influence of calcium chloride on strength of concrete made from five different cements was also studied.

Series 188.—Compression tests of 1:5 concrete cured at low temperatures at ages of 1 day to 3 months. In certain tests calcium chloride was used as admixture.

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Concrete and mortar tests were made in accordance with standardized methods. In general, each set included 5 to 10 concrete specimens or 5 mortar specimens made on different days.

The strength of concrete containing admixtures was compared with the strength of similar concrete without admixtures for the same mix, age, curing condition, etc.

The principal conclusions from these tests are:

1. Calcium chloride and the admixtures containing calcium chloride when used within certain limiting percentages, gave increased strength to concrete.

2. Magnesium chloride in flake form (46 per cent magnesium chloride, 54 per cent water) when used in concrete caused a reduction in strength except for small percentages, which showed a slight increase for 2 and 7-day tests.

3. The effect of the calcium-chloride admixtures in concrete varied with the type and quantity of admixture. When the tests are compared on the basis of chlorine content the different admixtures give similar results but not the same numerical values.

4. Calcium-chloride admixtures of the types used increased the strength of concrete approximately in proportion to the amount used up to a certain "optimum" percentage; the strength increase became less for further additions. Beyond a certain "critical" percentage further additions produced a reduction in strength as compared to similar concrete without admixtures.

5. Optimum and critical percentages for the calcium chloride admixtures used in these tests for 1:5.2 concrete of normal consistency and cured in moist room, were as follows:

Admixture	Per Cent of Admixture by Weight of Cement		Per Cent of Chlorine by Weight of Cement	
	Optimum	Critical	Optimum	Critical
Commercial Calcium Chloride A	2 to 4	6 to 8	1 to 2	3 to 4
Commercial Calcium Chloride B	2 to 4	6 to 8	1 to 2	3 to 4
Standard Cal	7 to 10	15 to 20	1 to 2	3 to 4
Low-Chlorine Cal	about 10	15 to 20	1 to 2	2 to 3
Vitriflux	6 to 8	10 to 15	1 to 2	2 to 3

6. The relative effectiveness of the different admixtures when compared on the basis of strength-ratio (the ratio of the strength of concrete containing admixture to that of similar concrete without admixture, expressed as a percentage) for the optimum percentages, is shown by the following strength-ratios, which are based on tests of 1:5.2 concrete of normal consistency cured in the moist room:

Admixture	Strength-Ratio for Optimum Percentage					
	2 days	7 days	28 days	3 mo.	1 yr.	3 yr.
Commercial Calcium Chloride A	170	125	110	112	117	118
Commercial Calcium Chloride B	147	124	109	109	119	116
Standard Cal	151	123	107	107	121	119
Low-Chlorine Cal	143	118	101	104	113	111
Vitriflux	138	115	106	108	109	114

7. The addition of calcium-chloride admixtures in amounts less than the "critical" percentage produced an increase in concrete strength that was practically constant at all ages. This constant strength increase, when expressed as a percentage of the strength of concrete without admixture, showed a diminishing ratio as the concrete gained in strength with age.

8. The addition of 2 per cent of calcium chloride to 1:5.2 concrete of the consistency ordinarily used in construction work (1.10 to 1.25) produced an increase in compressive strength of 100 to 200 lb. per sq. in. at ages of 2 days to 3 years; for 1.50 consistency there was little or no increase; for consistency 0.90 the increase was about 550 lb. per sq. in.

9. The increase in strength due to the addition of 2 per cent of commercial calcium chloride was practically negligible for a 1:7 mix; it increased with the cement content up to about a 1:4 mix; for mixes richer than 1:4 the strength increase remained about the same. The strength increase for the different mixes and the corresponding strength-ratios for ages of 2 days to 3 years were as follows:

Mix	Strength Increase, lb. per sq. in. (same for all ages)	Strength-Ratio, per cent (Fig. 4)				
		2 days	7 days	28 days	3 mo.	3 yr.
1:7	Negligible (±100)	115	107	85	88	95
1:5.2	400	138	125	107	110	110
1:4	700	148	130	119	117	115
1:3	1200	150	130	122	119	115
1:2	1300	149	130	122	120	105

10. The tests confirm the relation between water-cement ratio and compressive strength pointed out in other publications of this Laboratory. The water-ratio-strength curves for 2 per cent of commercial calcium chloride were similar in form to those for plain concrete but divergent at the lower water-ratios, showing the greater effect of the calcium chloride on the richer mixes and drier concretes.

11. The effect of commercial calcium chloride on the strength of concrete cured under different moisture conditions at normal tempera-

tures was slightly greater in concrete cured in the air of the laboratory than in concrete cured in water or in the moist room.

12. For concrete cured outdoors at temperatures near freezing, the use of 3 per cent of calcium chloride produced about the same strength increase as for other curing conditions. This strength increase appears as a much higher percentage gain when compared to the low strengths attained for outdoor curing. Too much dependence should not be placed on the use of calcium chloride for preventing freezing of concrete in cold weather; common salt should not be used for this purpose.

13. The cements used in the tests were in general similarly affected by addition of calcium chloride.

14. The effect of calcium chloride in mortar was essentially the same as in concrete.

15. The time of setting of the cement used was shortened by each of the admixtures. Flash set was produced by most of the admixtures when used in percentages somewhat in excess of those found to give greatest strength increases in concrete.

16. The important conclusion from these tests may be summarized as follows:

In the use of calcium chloride no advantage was gained for percentages of the commercial product greater than 2 or 3 per cent of the weight of cement; (chlorine content 1 to $1\frac{1}{2}$ per cent). This amount when used in mixes of about 1:5 and in consistencies suitable for building construction showed an increase in compressive strength of from 100 to 200 lb. per sq. in. which increase was practically constant at ages of 2 days to 3 years. For richer mixes and drier consistencies the strength increase was greater and for leaner mixes and wetter concretes it was less.

CALCIUM CHLORIDE AS AN ADMIXTURE IN CONCRETE

By Duff A. Abrams

Introduction

The use of chemical compounds for hastening the hardening of portland-cement concrete has attracted considerable interest during the past few years. Experience and earlier tests had shown that calcium chloride, or materials having this compound as one of their principal constituents, was probably the most promising for this purpose, and consequently the investigation of the effect of chemical admixtures on the compressive strength of concrete described in this report was confined primarily to such materials.

These tests were begun in cooperation with Committee C-9 on Concrete and Concrete Aggregates of the American Society for Testing Materials.[1] Our investigations covered a much wider range than originally outlined by the committee. They included tests of concrete at different ages for a wide range in mix, consistency and condition of curing, using different percentages of calcium chloride and other admixtures similar in type. A few tests were made using calcium chloride in concrete mixed and cured at low temperatures. This paper gives the results of about 7500 strength tests of concrete and mortar.

These tests were made as a part of the experimental studies of concrete and concrete materials being carried out at the Structural Materials Research Laboratory through the cooperation of Lewis Institute and the Portland Cement Association.

Outline of Tests

Three separate investigations were carried out:

Series 156 comprised compression tests of about 4000 6 by 12-in. concrete cylinders and 1250 2 by 4-in. mortar cylinders; specimens made June to August, 1921.

The following admixtures were used:

Calcium chloride *A*
Calcium chloride *B*
} Samples from different manufacturers
"Cal" furnished by Cal Chemical Co., Hagerstown, Md.
"Vitriflux" furnished by The Granitex Co., New York City.
Magnesium chloride, purchased in Chicago.

[1] See Report of Cooperative Series of Tests on Accelerators, *Proceedings*, Am. Soc. Testing Mats., Vol. 23, Part I. p. 223 (1923).

Concrete and mortar tests were made at ages ranging from 2 days to 3 years. The tests on calcium chloride *B* were extended to include wide variations in mixtures and consistencies and four different cements. Tables I to V, also VII, X, and XI, give the principal results of the tests in this series.

Series 158 consisted of compression tests of about 1700 6 by 12-in. concrete cylinders. Tests were made using 0 to 10 per cent of calcium chloride *B* by weight of cement for a wide range of periods of curing in the moist room, followed by air curing. Tests were made at ages of 7 days to $2\frac{1}{2}$ years. In one group five different cements were used. The specimens were made September to December, 1921. The test results of this series are given in Tables VI, VIII and XI.

Series 188 comprised 630 compression tests of 6 by 12-in. concrete cylinders made in a study of the early strength of concrete cured at low temperatures. Tests were made at ages of 1 day to 3 months for the following conditions:

(*a*) Specimens made in laboratory, cured in moist room,
(*b*) Specimens made in laboratory, cured outdoors,
(*c*) Specimens made outdoors, cured in moist room,
(*d*) Specimens made outdoors, cured outdoors.

The outdoor temperatures at the time the specimens were made (March 12 to 18, 1924) and for the following few days ranged from about 24 to 37° F. The indoor temperatures were about 68° F. This series of tests was carried out for the most part on concrete without admixtures but in some of the tests calcium chloride *A* was used in the proportion of 3 per cent by weight of the cement. Table IX gives the results of tests in this series.

MATERIALS AND METHODS

Cement.—All tests were made with portland cement purchased in Chicago. The physical tests of the cements are given in Table XIII; chemical analyses in Table XV. Cement A was used in Series 156, except in the tests of different cements, where brands B, C and D were also used. Most of the specimens in Series 158 and all of those in Series 188 were made with "Laboratory Cement," consisting of a mixture of four brands purchased in Chicago. In a part of Series 158, cements A, B, C, and D were used separately; these were the same brands used in Series 156 but from later lots.

Aggregate.—The aggregate for concrete consisted of sand and pebbles from Elgin, Ill., graded 0 to $1\frac{1}{2}$ in. It was screened into four sizes (0 to No. 4, No. 4 to $\frac{3}{8}$ in., $\frac{3}{8}$ to $\frac{3}{4}$ in. and $\frac{3}{4}$ to $1\frac{1}{2}$ in.) and recombined to a predetermined sieve analysis (fineness modulus 5.68). Aggre-

gates graded in this way are generally used in our laboratory to reduce the variations in grading to a minimum. The mortar tests in Series 156 were made using the same sand (graded 0 to No. 4, fineness modulus 3.04).

Admixtures.—Six different admixtures were used; two lots of commercial calcium chloride, Cal (standard and low chlorine), Vitriflux and magnesium chloride.

Two brands of commercial calcium chloride were obtained from different manufacturers and are designated as *A* and *B*. Brand *B* was used in most of the tests of both Series 156 and 158, although the lots used in the two series were purchased at different times. The commercial calcium chlorides contained about 75 per cent of $CaCl_2$ with small amounts of impurities, principally magnesium and sodium chloride; the magnesium chloride content was less than 0.5 per cent.

Two lots of Cal were used, standard and low chlorine. The material comes as a white powder. The standard contained about 25 per cent of calcium chloride, or about 16 per cent of chlorine; the low-chlorine Cal contained 17 per cent of calcium chloride, or 11 per cent of chlorine. For these tests the quantities are expressed as percentages of weight of cement. *Technologic Paper No. 174*, U. S. Bureau of Standards, 1920, "Effect of Cal as an Accelerator of the Hardening of Portland Cement Mixtures," by R. N. Young, states that "Cal is a material obtained by pulverizing the dried or undried product resulting from a mixture of either quicklime, or hydrated lime, calcium chloride, and water."

Vitriflux is a solution of calcium chloride in water (about 34 per cent of $CaCl_2$). The quantities of the liquid used are reported in the tables as percentages by weight of cement.

The magnesium chloride was of the grade commercially known as "flake" and contained about 46 per cent of $MgCl_2$.

Table XIV gives partial chemical analyses of the admixtures showing the amount of $CaCl_2$ and the combined chlorine.

Test Pieces.—The concrete specimens were 6 by 12-in. cylinders, and the mortar specimens were 2 by 4-in. cylinders. Concrete specimens were made in accordance with methods recommended in the Tentative Methods of Making Compression Tests of Concrete (Serial Designation: C 39 – 21 T) of the American Society for Testing Materials. The methods used in making the mortar specimens differed only in minor details from those outlined in the Tentative Specifications and Tests for Compressive Strength of Portland Cement Mortars (Serial Designation: C 9 – 16 T) of the American Society for Testing Materials.

The concrete cylinder forms were of cold-drawn steel tubing, slotted along one element. In making the specimens, the forms were placed on machined cast-iron plates. The concrete was placed in 3 layers, each layer being rodded 30 times with a $\frac{5}{8}$-in. bullet-pointed steel rod. The specimens were capped 3 to 4 hours after molding with neat cement (which had been allowed to stand 3 to 6 hours after mixing) and the caps brought to a true plane by means of machined plates which were worked down to the tops of the forms and left in place until the forms were removed after 16 to 20 hours.

Proportioning and Mixing.—In Series 156 and 158, each concrete specimen was made from a batch of about $\frac{1}{5}$ cu. ft., proportioned separately and mixed with a bricklayer's trowel in a shallow metal pan. The proportions of cement and aggregate are expressed as one volume of cement to a given number of volumes of dry, rodded aggregate[1] mixed as used. The quantities of each batch were determined by weight. For example, a batch of 1:5.2 concrete consisted of 3.82 lb. of cement, and 27.0 lb. of aggregate; the quantity of water varied from 2.00 to 2.50 lb. for concrete of normal consistency, depending on the kind and amount of admixture used.

In Series 188 the concrete was mixed with shovels on a metal plate in batches of sufficient size to make seven 6 by 12-in. cylinders.

The mortar specimens in Series 156 were of 1 : $2\frac{1}{2}$ mix by volume.

Consistency.—The plasticity of the concrete was measured by means of the "flow table"[2] using fifteen $\frac{1}{2}$-in. drops in 10 seconds. The test consists of jigging a truncated-cone-shaped mass of concrete on a special table, and measuring the bottom diameter after the test. The concrete was molded in a truncated cone having a top diameter of $6\frac{3}{4}$ in., a bottom diameter of 10 in., and a height of 5 in. The bottom diameter after the test, expressed as a percentage of the original diameter, is the "flow."

For relative consistency 1.00, sufficient water was used to give a flow of about 180. This represents a consistency such as would be used in machine-finished concrete road construction and corresponds to a slump of about $\frac{1}{2}$ to 1 in. For a relative consistency of 1.10,

[1] If these proportions are to be reduced to the common terms of separated volumes of damp aggregates measured loose, account must be taken of the differences in the volumes occupied by separated fine and coarse aggregate and the same materials when mixed. Account must also be taken of the bulking of the fine and coarse aggregate due to loose measurement and the presence of moisture. For example, a 1:5.2 mix based on dry and rodded mixed materials is approximately equivalent to a 1:2:4 mix of dry and rodded separated aggregates, which in turn is nearly the same as a 1: $2\frac{1}{2}$: $4\frac{1}{2}$ mixture in terms of the damp and loose materials commonly encountered in the field.

[2] For a description of the flow table see, "Time of Set of Concrete," by Watson Davis, *Proceedings* Am. Soc. Testing Mats., Vol. 21, p. 995 (1921).

10 per cent more water was used than for relative consistency 1.00; similarly for other consistencies.

Curing and Testing.—In general, the specimens for Series 156 were cured in a room in which the air was saturated with moisture and in which a uniform temperature of about 70° F. was maintained. For Series 158 and 188, specimens were cured in a moist room and in air as indicated in the tables.

Compression tests of concrete were made in a 200,000-lb. universal testing machine; mortar tests were made in a 40,000-lb. testing machine. The load was applied through a spherical bearing block placed on top of the specimen. The specimens having been carefully capped as previously described, no additional bedding was required.

DATA AND DISCUSSION

Outline of Results.—This report covers primarily an investigation of the effect of admixtures of commercial calcium chloride and of similar materials on the compressive strength of concrete made and cured under *normal temperature conditions.* In addition a few preliminary tests were made at temperatures near freezing. In view of the limited number of tests at low temperatures, the results cannot be considered as a comprehensive study of the value of calcium chloride for use in concrete work carried out in cold weather.

Some of the tests were made with proprietary compounds consisting essentially of a calcium chloride base. In one series, parallel tests were made with magnesium chloride.

This investigation does not cover the curing of concrete by spreading calcium chloride over the surface;[1] nor were any tests made to determine the merits of so-called "floor hardeners."

The effect of the various admixtures on the strength of concrete is discussed in relation to the usual considerations which arise in practice, such as differences in mix, consistency, curing, etc.

The following outline will facilitate the study of the test data; reference is made to the tables and diagrams which give the related data from the tests:

Type of Admixture:

Five different admixtures in varying amounts are compared using the same cement, mix, consistency and curing condition. Tests of concrete and mortar were made at ages of 2, 7 and 28 days, 3 months, 1 and 3 years; concrete cured in moist room and mortar in water, until tested. Tables I and II and Figs. 1 and 2 give the test results.

[1] For a discussion of this subject see, "An Investigation in the Use of Calcium Chloride as a Curing Agent and Accelerator of Concrete," by H. F. Clemmer and Fred Burggraf, *Proceedings*, Am. Soc. Testing Mats., Vol. 23, Part II, p. 296 (1923). Further field and laboratory tests of this kind are now under way by the Structural Materials Research Laboratory.

Quantity of Cement (Mix):

Five different mixes (1:7, 1:5.2, 1:4, 1:3 and 1:2) were used with the following percentages of calcium chloride *B*: 0, 1, 2, 4, 7 and 10. All specimens were mixed to a relative consistency of 1.00 and cured in the moist room until tested at ages of 2, 7, and 28 days, 3 months, 1 and 3 years. Table III and Figs. 3, 4, 6, 12 and 14 give the test results.

Quantity of Mixing Water (Consistency):

Five different consistencies (0.90, 1.00. 1.10, 1.25, and 1.50) were used with the following percentages of calcium chloride *B*: 0, 1, 2, 4, 7 and 10. Mix 1:5.2. All specimens were cured in the moist room until tested at ages of 2, 7, and 28 days, 3 months, 1 and 3 years. Table IV and Figs. 5, 6, 13 and 14 give the test results.

Water-Ratio-Strength Relation:

The different mixes and different consistencies indicated above provided concrete of a wide range in water-cement ratio. Data are given in Tables III and IV and in Fig. 6.

Curing Condition:

Specimens cured in moist room, water, and in air were compared in Series 156; Series 158 included specimens cured in moist room for a part of the curing period, remainder in air. Calcium chloride *B* was used in the following percentages: 0, 1, 2, 4, 7 and 10. In Series 156 all specimens were of 1:5.2 mix, relative consistency 1.00 and tested at 28 days, 3 months, 1 and 3 years. In Series 158 specimens were tested at 7 and 28 days, 3 and 6 months, 1 and 2½ years. Table V and Figs. 7 and 8 give results from Series 156. Table VI and Figs. 9 and 10 give results from Series 158.

Brand of Cement:

Tests of different cements were made in Series 156 using calcium chloride *B* in both concrete and mortar, and in Series 158 in concrete only. The same four brands of cement were used in both series but from different lots. Table VII and Fig. 11 give the results from Series 156 for 1:5.2 concrete and 1:2.5 mortar of relative consistency 1.00, tested at 2, 7 and 28 days, 3 months, 1 and 3 years with 0 and 4 per cent of calcium chloride. Table VIII gives the results from Series 158 for 1:5.2 concrete, relative consistency 1.00, tested at 28 days, 3 and 6 months, 1 and 2½ years, for percentages of calcium chloride of 0, 1, 2, 4, 7 and 10.

Age at Test:

In all of the studies of the effect of calcium chloride on the strength of concrete, the age at test is involved. The test data are considered with respect to the influence of the age at test on the action of the admixtures. Figs. 12, 13 and 14 show the results for tests of different mixes and consistencies. Fig. 15 shows the results for different admixtures.

Miscellaneous Tests:

These tests give data on the influence of calcium chloride on the time of setting of cement (Table XIV) on the "flow" (Table XII) and some data from tests of concrete made at low temperatures (Table IX and Fig. 16).

Summary Tables:

Tables X and XI summarize the results from Series 156 and 158.

Strength-Ratio.—In studying the effect of the various admixtures under the different conditions of test it is convenient to compare the strengths obtained with the strength of the corresponding concrete without admixture (here referred to as plain concrete). Thus, for each value of strength given in the tables there is a corresponding "strength-ratio," which expresses the strength as a percentage of the strength of the plain concrete, identical as to age, mix, consistency, brand of cement, and curing conditions. Obviously the strength-ratio for the plain concrete is 100 per cent.

The "maximum strength-ratios" given in Tables X and XI are the highest values shown by the curves representing the variation in strength due to the amount of admixture for the given set of conditions. In these two tables the per cent of admixture for which the highest values were found is also given.

Strength of Concrete Without Admixture.—The values for concrete strength are in general the average of 8 to 10 tests. In order to secure more reliable values for a basis of comparison the tests of plain concrete were duplicated at different points in Series 156; in some instances as many as 25 tests were averaged.

The average compressive strengths of 1:5.2 concrete of relative consistency 1.00 without admixtures were:

Series	Specimens Made	Compressive Strength, lb. per sq. in.						
		2 days	7 days	28 days	3 months	6 months	1 year	3 years
156	June–August, 1921.	950	1940	3310	4170	....	4320	5020
158	September–December, 1921.	...	1310	2640	3380	4110	4790	....

Tables III, IV, VII and VIII show the strengths for other mixes, consistencies, cements, etc.

Effect of Type of Admixture on the Strength of Concrete.—Figs. 1 and 2 show the effect of the different admixtures on the strength of concrete compared on the basis of the percentage of admixture and chlorine content. Fig. 1 shows that with the exception of magnesium chloride the different admixtures behave similarly, showing increases in strength up to a certain percentage of admixture beyond which the strength gradually decreased. The "optimum" percentages were not the same for the different admixtures. However, when comparisons are made on the basis of chlorine content as in Fig. 2, the high points of the curves fall approximately over each other, within the range of from 1 to 2 per cent of chlorine by weight of cement.

The increase in strength due to the different admixtures was not the same for the same percentages of chlorine, although for the

commercial brands of calcium chloride and standard Cal the results did not differ greatly.

The commercial samples of calcium chloride gave approximately the same results except for the 2-day tests, in which brand *A* gave somewhat higher strengths. The maximum strength-ratios were obtained with from 2 to 4 per cent of calcium chloride by weight of the cement. For quantities greater than about 4 per cent the strength gradually declined and fell below "par" at about 6 to 8 per cent by weight of cement; with 10 per cent of calcium chloride the strength-ratios ranged between 70 and 90 per cent.

The following maximum strength-ratios for calcium chlorides *A* and *B* in Series 156 and for *B* in Series 158, show the close agreement between the two brands and the separate lots of brand *B* tested at different times with different concrete materials.

Age at Test	Maximum Strength-Ratio, per cent			
	Series 156		Series 158	Average
	Calcium Chloride *A*	Calcium Chloride *B*	Calcium Chloride *B*	
2 days	170	147	...	158
7 days	125	124	123	124
28 days	110	109	106	108
3 months	112	109	108	110
1 year	117	119	96	111
3 years	118	116	...	117

More detailed discussions of the effect of calcium chloride are given below.

The effect of Cal on the strength of concrete was similar to that of commercial calcium chloride. The maximum acceleration in strength due to Cal was generally found at 7 and 10 per cent as compared with 2 to 4 per cent for commercial calcium chloride. The chlorine content of the optimum percentages of Cal and calcium chloride was about the same (1 to 2 per cent). See Tables I, II and X and Figs. 1 and 2. The maximum strength-ratios for standard Cal at different ages (Table X) were: 2 days, 151 per cent; 7 days, 123 per cent; 28 days, 107 per cent; 3 months, 107 per cent; 1 year, 121 per cent; 3 years, 119 per cent.

Vitriflux consisted of a 34 per cent solution of calcium chloride in liquid form which was placed in the mixing water in amounts corresponding to 1, 2, 4, 7, 10 and 15 per cent by weight of cement. The effectiveness of this material was approximately proportional to the amount added, up to about 7 per cent by weight of the cement, where the maximum strength was obtained. The following maximum

strength-ratios were found for about 7 per cent: 2 days, 138 per cent; 7 days, 115 per cent; 28 days, 106 per cent; 3 months 108 per cent; 1 year, 109 per cent; 3 years, 114 per cent. The chlorine content for 7 per cent of Vitriflux was approximately the same as for 2 to 4 per cent of commercial calcium chloride. At ages earlier than 28 days, the maximum effect of Vitriflux was considerably less than that shown by the average for calcium chloride. The strength-ratios for Vitriflux (7 per cent) were 138 per cent for 2 days and 115 per cent for 7 days as compared with 158 per cent and 124 per cent for the average of calcium chloride.

The magnesium chloride was received in flake form and was composed of about 46 per cent magnesium chloride and 54 per cent water. It was put into solution in the mixing water in amounts corresponding to 1, 2, 4, 7 and 10 per cent by weight of cement. In 1 : 5.2 concrete, magnesium chloride gave a slight increase in strength for the 1 and 2-per-cent admixture at 2 days and normal strength at 7 days but *reduced* the strength of concrete for all other conditions. At 28 days the strength-ratios were: 1 per cent magnesium chloride, 94 per cent; 2 per cent, 88 per cent; 4 per cent, 84 per cent; 7 per cent, 74 per cent; 10 per cent, 64 per cent. It will be seen by reference to Fig. 1 that the reduction in strength was approximately proportional to the quantity of magnesium chloride present.

Effect of Calcium Chloride as Influenced by the Quantity of Cement.—Table III and Figs. 3 and 12 give the results of compression tests of 5 different concrete mixtures using calcium chloride up to 10 per cent by weight of the cement. Fig. 3 shows that the strength of the concrete was increased at all ages by the addition of calcium chloride, except for the 1:7 mix at ages greater than 7 days. The maximum strength-ratios occurred at from 2 to 4 per cent for all mixes. For the 2-day tests, they were: 1:7 mix, 120 per cent; 1:5.2, 147 per cent; 1:4, 149 per cent; 1:3, 159 per cent; 1:2, 149 per cent.

Percentages of calcium chloride greater than 6 to 8 per cent *reduced* the strength at all ages.

Fig. 4 shows the relation of strength-ratio to cement content for 2 per cent of calcium chloride, the percentage for which the maximum values were generally obtained. With increase in the amount of cement up to 23.7 per cent of the volume of the concrete (1:4 mix) the strength-ratios increased at all ages; for the richer mixes the strength-ratios were practically constant for a given age.

In studying the effect of calcium chloride the gain in strength in *pounds per square inch*, as well as the *percentage* gain as measured by strength-ratio must be kept in mind. Reference to Table III and

Fig. 14 shows that the increases in strength in pounds per square inch at all ages for 2 per cent of calcium chloride were about as follows:

Mix	Relative Consistency	Increase in Strength, lb. per sq. in.
1:7	1.00	Shows a loss after 7 days
1:5.2	"	400
1:4	"	700
1:3	"	1200
1:2	"	1300

It is important to note that the increases in strength in pounds per square inch for a given mix are approximately constant for all ages.

Effect of Calcium Chloride as Influenced by Quantity of Mixing Water.—Table IV and Figs. 5 and 13 give the results of tests on concrete of 1:5.2 mix at ages of 2 days to 3 years for relative consistencies 0.90, 1.00, 1.10, 1.25, and 1.50. The "flows" for the first three consistencies were about 155, 170, and 205; the flow table was not large enough to permit of the determination of the flow for relative consistencies 1.25 and 1.50. The results of flow tests are given in Table XII.

For the 2 and 7-day tests the effect of calcium chloride as measured by the maximum strength-ratios, which in nearly every case corresponded to 2 per cent of admixture, was practically independent of the consistency of the concrete. At later ages the behavior was somewhat erratic and in general strength-ratios below 100 per cent were obtained with the wetter concretes for all percentages of calcium chloride. At 2 days the maximum strength-ratios were: relative consistency 0.90, 153 per cent; 1.00, 147 per cent; 1.10, 144 per cent; 1.25, 159 per cent; 1.50, 146 per cent (See Table XI). At 7 days the average of the maximum strength-ratios for all consistencies was about 120 per cent.

Water-Ratio-Strength Relation for Concrete.—The data obtained from the tests made on the concrete of different mixes and consistencies permits a study to be made of the general effect of quantity of mixing water on strength.

The results of tests on plain concrete and on concrete with 2 per cent of calcium chloride are plotted in Fig. 6 for ages of 2, 7 and 28 days, and 3 years. The curves for 3 months and 1 year were of similar form, but were omitted in order to avoid confusion. Similar curves may be drawn for other percentages of calcium chloride. In these tests the quantity of mixing water was varied by:

(*a*) Change in mix (relative consistency 1.00; Table III).
(*b*) Change in consistency (1:5.2 mix; Table IV).

The results of the tests are consistent and show the importance of the water-ratio-strength relation which has been pointed out in other publications of this laboratory. Increasing the quantity of mixing water produced exactly the same effect as reducing the quantity of cement in the batch. A 1:5.2 mix of relative consistency 1.25 (25 per cent more water than required for "normal" consistency) gave a strength at 28 days of 2100 lb. per sq. in. (See Fig. 6). This strength is about the same as that of a 1:6½ mix of relative consistency 1.00. A 1:5.2 mix of relative consistency 1.50, which is not as wet as concrete frequently used, gave a much lower strength than a 1:7 mix of relative consistency 1.00 ("normal" consistency).

The water-ratio-strength curves in Fig. 6 for concrete with 2 per cent of calcium chloride are similar in form to those for plain concrete. For the lower water-ratios (richer mixes and drier consistencies) the curves for 2 per cent calcium chloride show considerably higher strengths than the curves for plain concrete at all ages. However, the difference in strength becomes smaller as the water-ratio increases and at the later ages the strength for 2 per cent of calcium chloride is lower than that of the plain concrete.

Effect of Calcium Chloride as Influenced by Curing Condition.—Tests were carried out on concrete cured under different conditions. In Series 156 the following curing conditions were used for 1:5.2 concrete containing calcium chloride in amounts of from 1 to 10 per cent and tested at ages of 28 days to 3 years:

(*a*) Moist room,
(*b*) Water,
(*c*) Air of laboratory.

The results of these tests are given in Figs. 7 and 8. Fig. 7 shows that in general concrete cured in the moist room and in water had essentially the same strength at each age. In general the air-cured specimens gave considerably lower strengths than those cured in the moist room. At 28 days and 3 months, the differences in strength between the air-cured and moist-room-cured specimens decreased as calcium chloride was added. At 28 days, the air-cured specimens with 10 per cent calcium chloride were somewhat stronger than the specimens cured in water or moist room.

Fig. 8 shows that the strength-ratios for air-cured concrete containing 2 per cent of calcium chloride were about 125 per cent for all ages. The strength-ratios for moist-air and water curing were essentially the same at all ages and averaged about 108 per cent.

Fig. 9 gives the results from Series 158 for 1:5.2 concrete tested at ages ranging from 7 days to 2½ years. Calcium Chloride in per-

centages of from 0 to 10 per cent was used. These specimens were cured for periods in the moist room ranging from 0 days to 3 months followed by curing in the dry air of the laboratory. Curves for plain concrete and for concrete with 2 and 10 per cent of calcium chloride are shown. A striking parallelism between the curves for the plain concrete and those for concrete containing calcium chloride is evident for the different conditions of curing. It can also be shown by these curves that for certain combinations of moist-air curing followed by dry-air curing the strength is greater than when cured the entire period in moist air. This is in accordance with the results of other investigations which show that when the specimens are allowed to dry out before testing greater strengths are obtained. When the curing period in the moist room was relatively short compared to the age at test the curves show that moist-room curing gave the higher strengths.

The comparison between the relative effect of moist and dry curing on the action of calcium chloride can best be seen from Fig. 10, where it will be observed that at the later ages the effect of calcium chloride is somewhat more pronounced for air curing than for moist curing; at the early ages the effect of calcium chloride is about the same for both curing conditions.

Tests were made in Series 188 on the early strength of concrete made at low temperatures. Four separate conditions were used as follows:

Specimens made in the laboratory, cured in the moist room;
Specimens made in the laboratory, cured outdoors;
Specimens made outdoors, cured in the moist room;
Specimens made outdoors, cured outdoors.

A 1:5 concrete of relative consistency 1.25 (slump 8 in.) was used. The concrete was mixed in batches sufficient to make seven 6 by 12-in. concrete cylinders for test at ages of 1 day to 3 months. The outdoor temperatures during the time the specimens were made and for a few days following ranged from 24 to 37° F.; the indoor temperature was about 68° F. Parallel tests were made for plain concrete and for 3 per cent calcium chloride. Tests on effect of temperature of mixing water for concrete made outdoors and cured outdoors at low temperatures were also carried out. The results of these tests are given in Table IX; the results of the parallel tests using 0 and 3 per cent calcium chloride are shown in Fig. 16.

In Fig. 16, the Curve *S* for strength of concrete made in the laboratory and cured in the moist room at normal temperatures is taken as a standard for comparison, and to facilitate the study of the data is repeated in each of the small diagrams.

In general the calcium chloride specimens in this Series gave effects similar to those mentioned above. For the specimens made and cured outdoors at low temperatures, the calcium chloride seemed to be somewhat more effective although for this condition of test all of the strengths were low, as will be seen from the values in the following table:

Conditions of Test	Compressive Strength, lb. per sq. in.			
	2 days	7 days	28 days	3 months
Specimens made in laboratory, cured in moist room:				
0 per cent calcium chloride	410	1230	2640	4620
3 " " "	600	1260	2320	3670
Specimens made in laboratory, cured outdoors:				
0 per cent calcium chloride	100	430	1670	2930
3 " " "	200	750	1820	2670
Specimens made outdoors, cured in moist room:				
0 per cent calcium chloride	180	960	2680	4410
3 " " "	380	1010	2160	3440
Specimens made outdoors, cured outdoors:				
0 per cent calcium chloride	45	300	1660	2820
3 " " "	185	710	1980	2900

Table IX shows that the temperature of the concrete made and cured outdoors was not appreciably affected by the addition of calcium chloride.

Salts added to mixing water in freezing weather have two very different functions:

1. To depress the freezing point of the water slightly;

2. To accelerate the early hardening of the concrete with accompanying rise in temperature due to chemical reaction.

The following table shows the effect of certain percentages of common salt and calcium chloride on the freezing point of water:

Solution, per cent by weight	Freezing Point, deg. Fahr.	
	Common Salt	Calcium Chloride
0	32.0	32.0
1	30.5	31.1
2	29.3	30.4
5	25.2	27.7
10	18.7	21.4
15	6.1	−1.5

Five per cent of common salt lowers the freezing point about 6° F. However, tests made in this laboratory, reported elsewhere,[1] have shown that 5 per cent of common salt reduces the compressive strength of the concrete at 28 days about 30 per cent, and in the pre-

[1] Duff A. Abrams, "Tests of Impure Waters for Mixing Concrete." *Proceedings*, Am. Concrete Inst. (1924).

ceding discussion it has been shown that more than about 6 per cent of calcium chloride gives strengths below normal. It is evident, therefore, that dependence should not be placed on the lowered freezing point of the mixing water. In cold-weather work it is much more desirable to heat the materials and furnish proper protection and artificial heat to the structure, than to depend on chemical admixtures in the concrete.

Effect of Calcium Chloride as Influenced by Brand of Cement.—Calcium chloride *B* was used in parallel tests of concrete made from different brands of portland cement (A, B, C, D) in both Series 156 and 158; in Series 158 "Laboratory" cement made up of a mixture of equal parts of the same brands was also used. The two series of tests were made from different lots of cements. In general tests were made at ages of 2 days to 3 years. In Series 156 tests were made for 0 and 4 per cent of calcium chloride for moist-room curing (See Tables VII and XI and Fig. 11). In Series 158, calcium chloride was used in quantities ranging from 0 to 10 per cent by weight of cement for concrete cured 14 days in moist room, remainder in air of laboratory (See Tables VIII and XI).

The miscellaneous tests and chemical analyses of the cements are given in Tables XIII and XV.

Cements A, C and D and laboratory cement were affected similarly by calcium chloride. The behavior of cement B was somewhat erratic; in Series 156 this cement showed a slight increase in strength at 2 days, 1 and 3 years due to the addition of 4 per cent of calcium chloride and approximately normal strength at all other ages (See Fig. 11). This cement gave average concrete strengths at early ages, but abnormally high strengths at ages of 3 months to 3 years. In Series 158, cement B gave strength-ratios approximately the same as the other brands.

Effect of Calcium Chloride as Influenced by Age at Test.—In all of the tests the relation of age to strength is shown. It is of interest here to consider the influence of the age at test on the action of calcium chloride in concrete.

Fig. 12 gives data showing the relation of strength to age. Separate curves are plotted for each mix and amount of admixture (calcium chloride *B*). Similarly, Fig. 13 shows the data from the tests with varying quantity of mixing water. These curves are typical of all the data from these tests when plotted in the same manner and show that the strength of concrete is approximately proportional to the logarithm of the age at test.

Fig. 14 has been derived from the data of Figs. 12 and 13. It

shows a comparison of the age-strength relation of the plain concrete with concrete containing 2 per cent of calcium chloride for three different mixes of normal consistency and for four different consistencies of 1:5.2 mix. The diagrams show clearly the important fact that for all but the lean and wetter mixes the increase in strength produced by the addition of 2 per cent of calcium chloride when expressed in *pounds per square inch* was approximately constant for all ages of test. It is evident that the effect of calcium chloride is to produce an increase in strength at the early ages which is maintained throughout the later periods of test.

The following table gives the compressive strength of 1:5.2 concrete for relative consistency 1.00 at different ages (See Table I). The difference between the plain and treated concrete was approximately constant at all ages and averaged 400 lb. per sq. in.

Age at Test	Compressive Strength of Concrete, lb. per sq. in.			Strength-Ratios in terms of strength at 28 days, per cent	
	Plain	2 per cent Calcium Chloride, Average *A* and *B*	Difference	Plain	2 per cent Calcium Chloride
2 days	950	1400	450	29	40
7 days	1940	2410	470	59	68
28 days	3310	3530	220	100	100
3 months	4170	4460	290	126	127
1 year	4320	4850	530	131	138
3 years	5020	5470	450	152	155
			Av. 400		

It is interesting to note that the ratios of the strength at different ages to the 28-day strength for both plain concrete and concrete with 2 per cent of calcium chloride were essentially the same at ages greater than 28 days. At ages of 2 and 7 days, the treated specimens show a higher ratio to the 28-day strength than the plain.

Fig. 15 shows the variation of strength-ratios with age for three percentages of different types of admixtures. In general these include the optimum percentage, an intermediate percentage and the maximum percentage used. The strength-ratio was a maximum at the 2-day period in all cases, and decreased with age. The strength-ratios for the optimum percentage decreased more rapidly than for the less effective percentages. This decrease in strength-ratios is explained by the fact that the additional strength in pounds per square inch due to admixtures is approximately constant at all ages, so that when compared to the strength of the plain concrete which is increasing with age, the resulting strength-ratios become smaller.

Mortar Tests.—Tests of a 1:2½ mix by volume using sand graded up to the No. 4 sieve were made at ages of 2 days to 3 years (See Tables II, VII and X). At ages of 2 and 7 days the mortar tests gave essentially the same results as the concrete when admixtures of calcium chloride type were used. However, at the later ages the results were somewhat erratic. For example, calcium chloride *B* showed strength-ratios as low as 80 to 90 per cent. Specimens could not be made for calcium chloride (either *A* or *B*) for percentages of 7 per cent and higher due to the quick stiffening of the mortar.

Magnesium chloride showed an increase in strength in the mortar specimens at all ages as contrasted with the decrease in the case of the concrete specimens for ages greater than 7 days.

MISCELLANEOUS TESTS

Effect of Calcium Chloride on Plasticity of Concrete.—The proper quantity of mixing water or mixing solution was used in each case to produce concrete of the same plasticity as measured by the flow table. The plasticity of the concrete as measured by the flow and the corresponding water-ratios, are given in Table XII. The admixtures affected the quantity of water required to produce a constant flow only in so far as they caused the concrete to stiffen more quickly. Their effect, therefore, depended largely on the rapidity with which the flow test was carried out. In the case of the calcium chloride solutions the same quantity of mixing water was required to produce the same apparent plasticity and the same flow except in a few instances for the higher percentages where the concrete stiffened so rapidly that the values of the flow were erratic. For the magnesium chloride and Cal the quantity of mixing water required to maintain constant flow increased with the percentage of admixture. In the case of the Cal this was probably due to the fact that it contained considerable fine material (hydrated lime). It is not clear from the data of the flow tests or the time-of-setting tests why additional water was required for magnesium chloride and not for calcium chloride.

Normal Consistency.—The water required to produce normal consistency was determined for cement A in Series 156 when mixed with different percentages of admixtures. Normal consistency for the cement without admixtures required 23 per cent of water (See Table XIV). For 1 per cent of calcium chloride, in terms of the weight of the cement, 22 per cent of water was required to give normal consistency; with 2 per cent of calcium chloride about the same percentage was required as for cement without admixtures; with 4 per cent of calcium chloride 25 per cent of water was required. Tests could not be

made for higher percentages on account of flash set. The water required for normal consistency increased with the addition of Cal for all percentages used in these tests. The behavior of low-chlorine and standard Cal was essentially the same.

Vitriflux gave about the same results as calcium chloride in proportion to the amount of chlorine present.

Magnesium chloride also gave values approximately the same as calcium chloride except that higher percentages could be used without producing flash set.

Time of Setting.—Data on the time of setting of cement A using the different admixtures are shown in Table XIV. In general the time of setting was shortened by all of the admixtures. Calcium chloride A and B gave about the same results. For the percentage found to give best results in concrete (2 per cent) the time of final set was reduced from $3\frac{1}{2}$ to about 2 hours as determined with the Vicat needle, and from $5\frac{1}{2}$ to about 3 hours for the Gillmore needle.

With 7 per cent of Vitriflux, the optimum percentage in concrete, final set was attained in about $1\frac{1}{2}$ hours. With Cal of low chlorine content, 10 per cent gave a final set at about 2 hours. No time-of-setting tests were made with standard Cal. Flash set was produced by additions of calcium chloride greater than 4 per cent and for magnesium chloride and Vitriflux for additions greater than 7 per cent.

Soundness.—Table XIV gives data of standard soundness tests on cement A using the various admixtures. In all cases the cement passed the test satisfactorily.

Bibliography.—The attached bibliography lists the more important papers which contain information on the effect of calcium chloride as an admixture in cement and concrete.

The brief notes which accompany many of the references are meant to reflect the views expressed in the paper and do not indicate the opinion of the author of this report.

Related Tests.—We are now conducting field and laboratory experiments on the use of calcium chloride and other compounds as curing agents for concrete roads. Part of these tests are being made at Sacramento in cooperation with the California Highway Commission. This work will furnish the subject matter of a separate report.

A comprehensive report was recently published on tests of impure waters for mixing concrete. (*Proceedings*, American Concrete Institute, 1924, reprinted as Bulletin 12 of the Structural Materials Research Laboratory.) This report gives tests of concrete mixed with sulfate waters and solutions of common salt.

TABLE I.—EFFECT OF TYPE OF ADMIXTURE ON THE STRENGTH OF CONCRETE—SERIES 156.

Compression tests of 6 by 12-in. concrete cylinders.
Mix 1:5.2 by volume (1:2:4).
Aggregate: sand and pebbles from Elgin, Ill., graded 0 to 1½ in.
Cement: portland cement "A" purchased in Chicago.
Relative consistency 1.00 (Flow about 180, see Table XII).
Specimens cured in moist room until test; tested damp.
Each value is the average of from 4 to 10 tests made on different days unless otherwise noted.
Strength-ratios are percentages of the strength of concrete at same age without admixture.
Admixtures and chlorine expressed as per cent of weight of cement.
Data plotted in Figs, 1 and 2.

Admixture, per cent	Calcium Chloride A			Calcium Chloride B			Cal						Vitriflux			Magnesium Chloride		
							Low Chlorine			Standard								
	Chlorine, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Chlorine, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Chlorine, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Chlorine, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Chlorine, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Chlorine, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent
2-DAY TESTS																		
0[a]	0	950	100	0	950	100	0	950	100	0	950	100	0	950	100	0	950	100
1	0.5	1220	128	0.5	1220	128	0.1	....	....	....	....	....	0.2	1220	128	0.3	1090	115
2	1.0	1500	158	1.0	1310	138	0.2	1150	121	0.3	1120	118	0.4	1230	130	0.7	1060	111
4	1.9	1610	170	1.9	1400	147	0.4	1170	123	0.6	1300	137	0.9	1310	138	1.4	940	99
7	3.3	1070	113	3.4	960	101	0.7	1280	135	1.1	1430	151	1.5	1310	138	2.4	860	91
10	4.8	890	94	4.8	830	87	1.1	1360	143	1.6	1410	148	2.1	1230	130	3.4	700	74
15	...	....	...	...	....	...	1.6	1230	130	2.4	1230	129	3.2	1090	115	...	....	...
20	...	....	...	...	....	...	2.1	1100	116	3.2	1090	115	...	....	...	...	....	...
7-DAY TESTS																		
0[a]	0	1940	100	0	1940	100	0	1940	100	0	1940	100	0	1940	100	0	1940	100
1	0.5	2220	114	0.5	2120	109	0.1	....	....	....	....	....	0.2	2090	108	0.3	1970	102
2	1.0	2420	125	1.0	2400	124	0.2	2180	112	0.3	2060	106	0.4	2040	105	0.7	1880	97
4	1.9	2380	123	1.9	2220	114	0.4	2100	108	0.6	2280	118	0.9	2200	113	1.4	1800	93
7	3.3	1820	94	3.4	1700	88	0.7	2240	115	1.1	2390	123	1.5	2240	115	2.4	1580	81
10	4.8	1490	77	4.8	1560	80	1.1	2290	118	1.6	2260	117	2.1	2080	107	3.4	1380	71
15	...	....	...	...	....	...	1.6	2100	108	2.4	2130	110	3.2	1810	93	...	....	...
20	...	....	...	...	....	...	2.1	1830	94	3.2	1820	94	...	....	...	...	....	...
28-DAY TESTS																		
0[a]	0	3310	100	0	3310	100	0	3310	100	0	3310	100	0	3310	100	0	3310	100
1	0.5	3230	98	0.5	3240	98	0.1	....	....	....	....	....	0.2	3220	97	0.3	3090	94
2	1.0	3630	110	1.0	3430	104	0.2	3310	100	0.3	3070	93	0.4	3150	95	0.7	2920	88
4	1.9	3620	109	1.9	3620	109	0.4	3330	100	0.6	3320	100	0.9	3500	106	1.4	2780	84
7	3.3	2950	89	3.4	2890	87	0.7	3340	101	1.1	3550	107	1.5	3490	105	2.4	2450	74
10	4.8	2520	76	4.8	2460	74	1.1	3300	100	1.6	3540	107	2.1	3140	95	3.4	2120	64
15	...	....	...	...	....	...	1.6	3200	97	2.4	3100	94	3.2	3010	91	...	....	...
20	...	....	...	...	....	...	2.1	2910	88	3.2	2770	84	...	....	...	...	....	...
3-MONTH TESTS																		
0[a]	0	4170	100	0	4170	100	0	4170	100	0	4170	100	0	4170	100	0	4170	100
1	0.5	4160	100	0.5	4060	97	0.1	....	....	....	....	....	0.2	4210	101	0.3	3980	95
2	1.0	4450	107	1.0	4470	107	0.2	4130	99	0.3	4050	97	0.4	4110	99	0.7	3800	91
4	1.9	4670	112	1.9	4550	109	0.4	4190	101	0.6	4390	105	0.9	4260	102	1.4	3650	88
7	3.3	3980	95	3.4	3780	91	0.7	4260	102	1.1	4430	106	1.5	4500	108	2.4	3400	82
10	4.8	3330	80	4.8	3320	80	1.1	4330	104	1.6	4460	107	2.1	4040	97	3.4	2840	68
15	...	....	...	...	....	...	1.6	4160	100	2.4	4180	100	3.2	3800	91	...	....	...
20	...	....	...	...	....	...	2.1	3900	94	3.2	3840	92	...	....	...	...	....	...
1-YEAR TESTS																		
0[a]	0	4320	100	0	4320	100	0	4320	100	0	4320	100	0	4320	100	0	4320	100
1	0.5	4340	100	0.5	4480	104	0.1	....	....	....	....	....	0.2	4380	101	0.3	4100	95
2	1.0	4900	114	1.0	4790	111	0.2	4370	101	0.3	4590	106	0.4	4730	109	0.7	4320	100
4	1.9	5060	117	1.9	5130	119	0.4	4460	103	0.6	5000	116	0.9	4720	109	1.4	4160	96
7	3.3	4630	107	3.4	4510	104	0.7	4160	103	1.1	5190	120	1.5	4640	107	2.4	3870	90
10	4.8	3810	88	4.8	3870	90	1.1	4880	113	1.6	5220	121	2.1	4640	107	3.4	3250	75
15	...	....	...	...	....	...	1.6	4610	107	2.4	4730	109	3.2	4580	106	...	....	...
20	...	....	...	...	....	...	2.1	4450	103	3.2	4510	104	...	....	...	...	....	...
3-YEAR TESTS																		
0[a]	0	5020	100	0	5020	100	0	5020	100	0	5020	100	0	5020	100	0	5020	100
1	0.5	5170	103	0.5	4680	93	0.1	....	....	....	....	....	0.2	4940	98	0.3	4710	94
2	1.0	5400	108	1.0	5540	110	0.2	5130	102	0.3	5140	102	0.4	4940	98	0.7	4830	96
4	1.9	5900	118	1.9	5840	116	0.4	5050	101	0.6	5100	102	0.9	5330	106	1.4	4650	93
7	3.3	5210	104	3.4	5040	100	0.7	5440	108	1.1	5980	119	1.5	5710	114	2.4	4500	90
10	4.8	4490	89	4.8	4590	91	1.1	5340	106	1.6	5750	115	2.1	5510	110	3.4	3950	79
15	...	....	...	...	....	...	1.6	5550	111	2.4	5270	105	3.2	5360	107	...	....	...
20	...	....	...	...	....	...	2.1	5330	106	3.2	5050	101	...	....	...	...	....	...

[a] All values average of 25 tests.

TABLE II.—EFFECT OF TYPE OF ADMIXTURE ON THE STRENGTH OF MORTAR—SERIES 156.

Compression tests of 2 by 4-in. mortar cylinders.
Mix 1:2.5 by volume.
Aggregate: sand from Elgin, Ill., graded 0 to No. 4.
Cement: portland cement "A" purchased in Chicago.
Relative consistency 1.00 (Flow about 130, see Table XII).
Specimens cured in water until test; tested damp.
Each value is the average of 5 tests made on different days unless otherwise noted.
Strength-ratios are percentages of strength of mortar at same age without admixture.
Admixture and chlorine expressed as per cent of weight of cement.

Admixture, per cent	Calcium Chloride A			Calcium Chloride B			Cal						Vitriflux			Magnesium Chloride		
							Low Chlorine			Standard								
	Chlorine, per cent	Compressive Strength, lb. per sq. in.	Strength-ratio, per cent	Chlorine, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Chlorine, per cent	Compressive Strength, lb. per sq. in.	Strength-ratio, per cent	Chlorine, per cent	Compressive Strength, lb. per sq. in.	Strength-ratio, per cent	Chlorine, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Chlorine, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent
2-DAY TESTS																		
0[a]	0	1970	100	0	1970	100	0	1970	100	0	1970	100	0	1970	100	0	1970	100
1	0.5	2710	138	0.5	2500	127	0.1	....	....	....	....	....	0.2	2490	126	0.3	2350	119
2	1.0	2880	146	1.0	2550	130	0.2	2230	113	0.3	2730	139	0.4	2650	135	0.7	2590	131
4	1.9	2610	132	1.9	2290	116	0.4	2530	128	0.6	2910	148	0.9	2920	148	1.4	2260	115
7	...	[b]	...	...	[b]	...	0.7	2680	136	1.1	3190	162	1.5	2580	131	2.4	2010	102
10	...	....	...	...	....	...	1.1	2730	139	1.6	2950	150	2.1	2370	120	...	[b]	...
15	...	....	...	...	....	...	1.6	2580	131	2.4	2770	141	...	[b]	...	...	....	...
20	...	....	...	...	....	...	2.1	2370	120	3.2	2420	123	...	....	...	...	....	...
7-DAY TESTS																		
0[a]	0	3610	100	0	3610	100	0	3610	100	0	3610	100	0	3610	100	0	3610	100
1	0.5	3800	105	0.5	3960	110	0.1	....	....	....	....	....	0.2	3610	100	0.3	3750	104
2	1.0	4320	120	1.0	3920	109	0.2	3560	99	0.3	4210	117	0.4	3970	110	0.7	4040	112
4	1.9	3900	108	1.9	3640	101	0.4	3950	109	0.6	4580	127	0.9	4620	128	1.4	4000	111
7	...	[b]	...	...	[b]	...	0.7	4080	113	1.1	4930	136	1.5	4410	122	2.4	3430	95
10	...	....	...	...	....	...	1.1	4480	124	1.6	4730	131	2.1	3840	106	...	[b]	...
15	...	....	...	...	....	...	1.6	4090	113	2.4	3500	97	...	[b]	...	...	....	...
20	...	....	...	...	....	...	2.1	3500	97	3.2	3260	90	...	....	...	...	....	...
28-DAY TESTS																		
0[a]	0	5100	100	0	5100	100	0	5100	100	0	5100	100	0	5100	100	0	5100	100
1	0.5	5400	106	1.5	5020	98	0.1	....	....	....	....	....	0.2	5450	107	0.3	5070	99
2	1.0	5560	109	1.0	5010	98	0.2	5330	105	0.3	5470	107	0.4	5700	112	0.7	5410	106
4	1.9	5250	103	1.9	4570	90	0.4	5450	107	0.6	5940	116	0.9	5800	114	1.4	5490	108
7	...	[b]	...	...	[b]	...	0.7	5440	107	1.1	6200	122	1.5	5460	107	2.4	4770	94
10	...	....	...	...	....	...	1.1	5390	106	1.6	5400	106	2.1	4700	92	...	[b]	...
15	...	....	...	...	....	...	1.6	5190	102	2.4	5540	109	...	[b]	...	...	....	...
20	...	....	...	...	....	...	2.1	4960	97	3.2	4700	92	...	....	...	...	....	...
3-MONTH TESTS																		
0[a]	0	6080	100	0	6080	100	0	6080	100	0	6080	100	0	6080	100	0	6080	100
1	0.5	5580	92	0.5	5749	94	0.1	....	....	....	....	....	0.2	5750	94	0.3	6310	104
2	1.0	6490	107	1.0	5790	95	0.2	6030	99	0.3	6390	105	0.4	5230	86	0.7	6700	110
4	1.9	6010	99	1.9	5180	85	0.4	6490	107	0.6	7030	116	0.9	6550	108	1.4	6470	106
7	...	[b]	...	...	[b]	...	0.7	6470	106	1.1	7420	122	1.5	6550	108	2.4	5950	98
10	...	....	...	...	....	...	1.1	6320	104	1.6	6810	112	2.1	4820	79	...	[b]	..
15	...	....	...	...	....	...	1.6	6350	104	2.4	6250	103	...	[b]	...	...	....	...
20	...	....	...	...	....	...	2.1	5800	95	3.2	4960	81	...	....	...	...	....	...
1-YEAR TESTS																		
0[a]	0	6520	100	0	6520	100	0	6520	100	0	6520	100	0	6520	100	0	6520	100
1	0.5	5840	90	0.5	6110	98	0.1	....	....	....	....	....	0.2	6540	100	0.3	7510	115
2	1.0	6930	106	1.0	6110	94	0.2	6550	100	0.3	7130	109	0.4	6640	102	0.7	6940	106
4	1.9	5800	89	1.9	5300	81	0.4	6710	103	0.6	7750	119	0.9	7050	108	1.4	7110	109
7	...	[b]	...	...	[b]	...	0.7	6150	94	1.1	7900	121	1.5	6630	102	2.4	6180	95
10	...	....	...	...	....	...	1.1	7880	121	1.6	7150	109	2.1	5600	86	...	[b]	...
15	...	....	...	...	....	...	1.6	6880	105	2.4	6760	104	...	[b]	...	...	....	...
20	...	....	...	...	....	...	2.1	6510	100	3.2	6670	102	...	....	...	...	....	...
3-YEAR TESTS																		
0[a]	0	6820	100	0	6820	100	0	6820	100	0	6820	103	0	6820	100	0	6820	100
1	0.5	7240	106	0.5	6430	94	0.1	....	....	....	....	....	0.2	7030	103	0.3	7480	110
2	1.0	5440	80	1.0	6560	96	0.2	6220	91	0.3	7620	112	0.4	6950	102	0.7	7180	105
4	1.9	5870	86	1.9	5590	82	0.4	6050	89	0.6	7980	117	0.9	6640	97	1.4	6920	102
7	...	[b]	..	...	[b]	...	0.7	6700	98	1.1	8840	130	1.5	6490	95	2.4	7250	106
10	...	....	..	...	....	..	1.1	7360	108	1.6	8770	129	2.1	6030	89	...	[b]	...
15	...	....	...	...	....	..	1.6	6660	98	2.4	7590	111	...	[b]	...	...	....	...
20	...	....	...	...	....	...	2.1	7230	106	3.2	6940	102	...	....	...	...	....	...

[a] All values average of 15 tests.
[b] Unable to make specimens with higher percentages due to quick stiffening.

Table III.—Effect of Calcium Chloride on the Strength of Concrete as Influenced by Mix—Series 156.

Compression tests of 6 by 12-in. concrete cylinders.
Mix by volume.
Aggregate: sand and pebbles from Elgin, Ill., graded 0 to 1½ in.
Cement: portland cement "A" purchased in Chicago.
Relative consistency 1.00 (Flow about 180, see Table XII).
Specimens cured in moist room until test; tested damp.
Each value is the average of 5 tests made on different days unless otherwise noted.
Strength-ratios are percentages of the strength of concrete at same age without calcium chloride.
Data plotted in Figs. 3, 4, 6, 12 and 14.

Calcium Chloride *B*, per cent	Chlorine, per cent[a]	Mix 1:7			Mix 1:5.2			Mix 1:4			Mix 1:3			Mix 1:2		
		$CaCl_2$[b]	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	$CaCl_2$[b]	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	$CaCl_2$[b]	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	$CaCl_2$[b]	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	$CaCl_2$[b]	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent
2-day Tests																
0	0	0	540	100	0	950[c]	100	0	1350	100	0	1960	100	0	2780	100
1	0.5	1.4	630	117	1.8	1220[d]	128	2.0	1660	123	2.3	2510	128	3.1	3520	126
2	1.0	2.7	620	115	3.7	1310[d]	138	4.3	2010	149	5.3	3110	159	6.4	4150	149
4	1.9	5.5	650	120	7.8	1400[d]	147	8.9	1960	145	11.0	2790	142	12.9	3550	128
7	3.4	10.0	560	104	13.4	960[d]	101	16.5	1480	110	19.9	1920	98	20 2	2020	73
10	4.8	14.9	590	109	19.8	830[d]	87	22.5	1040	77	29.5	1740	89	31.6	1670	60
7-day Tests																
0	0	0	1100	100	0	1940[c]	100	0	2660	100	0	3680	100	0	4530	100
1	0.5	1.4	1140	104	1.8	2120[d]	109	2.0	2970	111	2.3	3920	106	3.1	5290	116
2	1.0	2.7	1160	106	3.7	2400[d]	124	4.3	3450	130	5.3	4760	130	6.4	5890	130
4	1.9	5.5	1160	106	7.8	2200[d]	114	8.9	3170	119	11.0	4620	125	12.9	5280	116
7	3.4	10.0	990	90	13.4	1700[d]	88	16.5	2520	94	19.9	3440	93	20.2	3500	77
10	4.8	14.9	930	85	19.8	1560[d]	80	22.5	1780	67	29.5	3030	82	31.6	2820	62
28-day Tests																
0	0	0	2060	100	0	3310[c]	100	0	4240	100	0	4920	100	0	5750	100
1	0.5	1.4	1780	86	1.8	3240[d]	98	2.0	4210	99	2.3	5200	106	3.1	6500	113
2	1.0	2.7	1710	83	3.7	3430[d]	104	4.3	4900	116	5.3	6160	125	6.4	7070	123
4	1.9	5.5	1840	89	7.8	3620[d]	109	8.9	4490	106	11.0	6280	128	12.9	6510	113
7	3.4	10.0	1650	80	13.4	2890[d]	87	16.5	3960	93	19 9	4510	92	20.2	5400	94
10	4.8	14.9	1610	78	19.8	2460[d]	74	22.5	2920	69	29.5	4090	83	31.6	4870	85
3-month Tests																
0	0	0	2790	100	0	4170[c]	100	0	5140	100	0	5960	100	0	6140	100
1	0.5	1.4	2490	89	1.8	4060[d]	97	2.0	5280	103	2.3	6220	104	3.1	6910	113
2	1.0	2.7	2430	87	3.7	4470[d]	107	4 3	5750	112	5.3	7070	118	6.4	7590	124
4	1.9	5.5	2520	90	7.8	4550[d]	109	8.9	5670	110	11.0	6920	116	12 9	8030	131
7	3.4	10.0	2400	86	13.4	3780[d]	91	16.5	5050	98	19.9	5700	96	20.2	6740	110
10	4.8	14.9	2180	78	19.8	3320[d]	80	22.5	3980	77	29.5	5670	95	31.6	5800	95
1-year Tests																
0	0	0	3050	100	0	4320[c]	100	0	5750	100	0	6490	100	0	7090	100
1	0.5	1.4	2810	92	1.8	4480[d]	104	2.0	5790	101	2.3	6730	104	3.1	7410	105
2	1.0	2.7	2870	94	3.7	4790[d]	111	4.3	6340	110	5.3	7270	112	6.4	7570	106
4	1 9	5.5	2730	90	7.8	5130[d]	119	8.9	6260	109	11.0	7320	113	12.9	7620	107
7	3.4	10.0	2840	93	13.4	4510[d]	104	16.5	5650	98	19 9	6240	96	20.2	6820	96
10	4.8	14.9	2810	92	19.8	3870[d]	90	22.5	4300	75	29.5	5690	88	31.6	5530	78
3-year Tests																
0	0	0	3500	100	0	5020[c]	100	0	6390	100	0	7530	100	0	8390	100
1	0.5	1.4	3360	96	1.8	4680[d]	93	2.0	6490	102	2.3	7840	104	3.1	8870	106
2	1.0	2.7	3240	93	3.7	5540[d]	110	4.3	7210	113	5.3	8710	116	6.4	8940	107
4	1.9	5.5	3080	88	7.8	5840[d]	116	8.9	6980	109	11.0	8470	112	12.9	8970	107
7	3.4	10.0	3220	92	13.4	5040[d]	100	16.5	6090	95	19.9	6170	82	20.2	6990	83
10	4.8	14.9	3020	86	19.8	4590[d]	91	22.5	5360	84	29.5	5850	78	31.6	5160	62

[a] Per cent of weight of cement.
[b] Per cent of weight of mixing water using commercial product.
[c] Average of 25 tests
[d] Average of 10 tests

TABLE IV.—EFFECT OF CALCIUM CHLORIDE ON THE STRENGTH OF CONCRETE AS INFLUENCED BY CONSISTENCY—SERIES 156.

Compression tests of 6 by 12-in. concrete cylinders.
Mix 1:5.2 by volume (1:2:4).
Aggregate: sand and pebbles from Elgin, Ill., graded 0 to 1½ in.
Cement: portland cement "A" purchased in Chicago.
Specimens cured in moist room until test; tested damp.
Each value is the average of 5 tests made on different days unless otherwise noted.
Strength-ratios are percentages of strength of concrete at same age without calcium chloride.
Data plotted in Figs. 5, 6, 13 and 14.

Calcium Chloride *B*, per cent[a]	Chlorine, per cent[a]	Relative Consistency of Concrete: 0.90			1.00			1.10			1.25			1.50[e]		
		$CaCl_2$[b]	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	$CaCl_2$[b]	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	$CaCl_2$[b]	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	$CaCl_2$[b]	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	$CaCl_2$[b]	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent
2-DAY TESTS																
0	0	0	1110	100	0	950[c]	100	0	720	100	0	440	100	0	280	100
1	0.5	2.0	1540	139	1.8	1220[d]	128	1.6	920	128	1.4	560	127	1.2	360	128
2	1.0	4.0	1700	153	3.7	1310[d]	138	3.2	1040	144	2.9	700	159	2.4	410	146
4	1.9	8.1	1610	145	7.8	1400[d]	147	6.6	980	136	5.8	670	152	4.8	400	143
7	3.4	14.7	1190	107	13.4	960[d]	101	11.8	780	108	10.4	510	116	8.5	400	143
10	4.8	21.5	940	85	19.8	830[d]	87	17.3	590	82	15.1	430	98	12.4	360	128
7-DAY TESTS																
0	0	0	2370	100	0	1940[c]	100	0	1560	100	0	1070	100	0	640	100
1	0.5	2.0	2590	109	1.8	2120[d]	109	1.6	1630	104	1.4	1150	107	1.2	670	105
2	1.0	4.0	2750	116	3.7	2400[d]	124	3.2	1790	115	2.9	1250	117	2.4	780	122
4	1.9	8.1	2660	112	7.8	2220[d]	114	6.6	1770	113	5.8	1150	107	4.8	780	122
7	3.4	14.7	2250	95	13.4	1700[d]	88	11.8	1370	88	10.4	930	87	8.5	720	112
10	4.8	21.5	1780	75	19.8	1560[d]	80	17.3	1100	70	15.1	820	77	12.4	630	98
28-DAY TESTS																
0	0	0	3830	100	0	3310[c]	100	0	2750	100	0	2100	100	0	1200	100
1	0.5	2.0	3740	98	1.8	3250[d]	98	1.6	2580	94	1.4	1810	86	1.2	1270	106
2	1.0	4.0	3830	100	3.7	3430[d]	104	3.2	2710	99	2.9	2020	96	2.4	1280	107
4	1.9	8.1	3850	100	7.8	3620[d]	109	6.6	2770	101	5.8	1830	87	4.8	1260	105
7	3.4	14.7	3310	86	13.4	2890[d]	87	11.8	2290	83	10.4	1700	81	8.5	1210	101
10	4.8	21.5	2770	72	19.8	2460[d]	74	17.3	1980	72	15.1	1570	75	12.4	1200	100
3-MONTH TESTS																
0	0	0	4590	100	0	4170[c]	100	0	3830	100	0	2840	100	0	1860	100
1	0.5	2.0	4610	101	1.8	4060[d]	97	1.6	3490	91	1.4	2660	94	1.2	1720	92
2	1.0	4.0	4670	102	3.7	4470[d]	107	3.2	3860	101	2.9	2680	94	2.4	1800	97
4	1.9	8.1	4780	104	7.8	4550[d]	109	6.6	3490	91	5.8	2510	88	4.8	1850	99
7	3.4	14.7	4200	91	13.4	3780[d]	91	11.8	3220	84	10.4	3250	79	8.5	1690	91
10	4.8	21.5	3810	83	19.8	3320[d]	80	17.3	2640	69	15.1	2080	73	12.4	1580	85
1-YEAR TESTS																
0	0	0	4450	100	0	4320[c]	100	0	4030	100	0	3060	100	0	2080	100
1	0.5	2.0	4730	106	1.8	4480[d]	104	1.6	4030	100	1.4	2800	92	1.2	2030	98
2	1.0	4.0	5620	126	3.7	4790[d]	111	3.2	4160	103	2.9	3050	100	2.4	2020	97
4	1.9	8.1	5240	118	7.8	5130[d]	119	6.6	4250	105	5.8	3060	100	4.8	2140	103
7	3.4	14.7	4590	103	13.4	4510[d]	104	11.8	3760	93	10.4	2720	89	8.5	2090	101
10	4.8	21.5	4180	94	19.8	3870[d]	90	17.3	3440	85	15.1	2680	88	12.4	2170	104
3-YEAR TESTS																
0	0	0	5170	100	0	5020[c]	100	0	4480	100	0	3460	100	0	2400	100
1	0.5	2.0	5270	102	1.8	4680[d]	93	1.6	4370	97	1.4	3070	89	1.2	2330	97
2	1.0	4.0	5860	113	3.7	5540[d]	110	3.2	4600	103	2.9	3510	102	2.4	2310	96
4	1.9	8.1	5980	116	7.8	5840[d]	116	6.6	4990	111	5.8	3410	99	4.8	2310	96
7	3.4	14.7	5830	113	13.4	5040[d]	100	11.8	4450	99	10.4	3300	95	8.5	2190	91
10	4.8	21.5	4890	95	19.8	4590[d]	91	17.3	3850	86	15.1	3020	87	12.4	2180	91

[a] Per cent of weight of cement.
[b] Per cent of weight of mixing water based on the commercial product.
[c] Average of 25 tests
[d] Average of 10 tests.
[e] Average of 4 tests.

TABLE V.—EFFECT OF CALCIUM CHLORIDE ON THE STRENGTH OF CONCRETE AS INFLUENCED BY DIFFERENT CURING CONDITIONS—SERIES 156.

Compression tests of 6 by 12-in. concrete cylinders.
Mix 1:5.2 by volume (1:2:4).
Aggregate: sand and pebbles from Elgin, Ill., graded 0 to 1½ in.
Cement: portland cement "A" purchased in Chicago.
Relative consistency 1.00 (Flow about 180, see Table XII).
Each value is the average of 9 tests made on different days, unless otherwise noted.
Strength-ratios are percentages of strength of concrete at same age without calcium chloride.
Calcium chloride and chlorine expressed as per cent of weight of cement.
Data plotted in Figs. 7 and 8. Compare Table VI.

Calcium Chloride *B*, per cent	Chlorine, per cent	Moist-Room Curing[a]		Water Curing		Air Curing	
		Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent
28-DAY TESTS							
0	0	3310[b]	100	3140	100	2600	100
1	0.5	3240[c]	98	3160	101	2820	108
2	1.0	3430[c]	104	3440	110	3120	120
4	1.9	3620[c]	109	3210	102	3170	122
7	3.4	2890[c]	87	2620	83	2910	112
10	4.8	2460[c]	74	2630	84	2860	110
Average		3160	95	3030	97	2910	112
3-MONTH TESTS							
0	0	4170[b]	100	4080	100	2950	100
1	0.5	4060[c]	97	4100	101	3260	111
2	1.0	4470[c]	107	4330	106	3560	121
4	1.9	4550[c]	109	4260	104	3370	114
7	3.4	3780[c]	91	3770	92	3190	108
10	4.8	3320[c]	80	3590	88	3230	110
Average		4060	97	4020	99	3260	111
1-YEAR TESTS							
0	0	4320[b]	100	4520	100	2660	100
1	0.5	4480[c]	104	4520	100	3090	116
2	1.0	4790[c]	111	4890	108	3270	123
4	1.9	5130[c]	119	4690	104	3240	122
7	3.4	4510[c]	104	4330	96	2760	104
10	4.8	3870[c]	90	4350	96	2840	107
Average		4520	105	4550	101	2980	112
3-YEAR TESTS							
0	0	5020[b]	100	4720	100	2990	100
1	0.5	4680[c]	93	4990	106	3280	110
2	1.0	5540[c]	110	5080	108	3680	123
4	1.9	5840[c]	116	5180	110	3390	113
7	3.4	5040[c]	100	5240	111	3240	108
10	4.8	4590[c]	91	4700	100	3020	101
Average		5120	102	4970	106	3270	109

[a] Same values used in Table I.
[b] Average of 25 tests.
[c] Average of 10 tests

Table VI.—Effect of Calcium Chloride on the Strength of Concrete as Influenced by Different Curing Conditions—Series 158.

Compression tests of 6 by 12-in. concrete cylinders.
Mix 1:5.2 by volume (1:2:4).
Aggregate: sand and pebbles from Elgin, Ill., graded 0 to 1½ in.
Cement: a mixture of four brands of portland cement purchased in Chicago (Laboratory cement).
Relative consistency 1.00 (Flow about 180, see Table XII).
Each value is the average of 5 tests made on different days.
Strength-ratios are percentages of strength of concrete at same age without calcium chloride.
Calcium chloride expressed in terms of weight of cement.
Data plotted in Figs. 9 and 10.

Calcium Chloride *B*, per cent	Cured in Moist Room for Periods Indicated; Remainder in Air															
	0		3 Days		7 Days		14 Days		28 Days		3 Months		6 Months		1 Year	
	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent
7-day Tests																
0	1340	100	1450	100	1310	100	....	...	....	...	....	...	....	...	....	...
1	1580	118	1600	110	1530	117	....	...	....	...	....	...	....	...	....	...
2	1660	124	1830	126	1610	123	....	...	....	...	....	...	....	...	....	...
4	1800	134	1830	126	1530	117	....	...	....	...	....	...	....	...	....	...
7	1580	118	1680	116	1270	97	....	...	....	...	....	...	....	...	....	...
10	1550	116	1580	109	1180	90	....	...	....	...	....	...	....	...	....	...
Average	1590	119	1660	114	1400	107	....	...	....	...	....	...	....	...	....	...
28-day Tests																
0	2080	100	2220	100	2720	100	2650	100	2640	100	....	...	....	...	....	...
1	2270	109	2450	110	2860	105	2830	107	2610	99	....	...	....	...	....	...
2	2290	110	2640	119	2980	110	3200	121	2810	106	....	...	....	...	....	...
4	2470	119	2710	122	3040	112	3100	117	2560	97	....	...	....	...	....	...
7	2330	112	2530	114	2870	105	3000	113	2250	85	....	...	....	...	....	...
10	2360	113	2480	112	2750	101	2770	104	2030	77	....	...	....	...	....	...
Average	2300	111	2600	113	2870	105	2920	110	2490	94	....	...	....	...	....	...
3-month Tests																
0	2530	100	2630	100	3110	100	3500	100	4120	100	3380	100	....	...	....	...
1	2580	102	2660	101	3450	111	3670	105	4020	97	3560	105	....	...	....	...
2	2750	108	3170	121	3610	116	3670	105	4100	100	3640	108	....	...	....	...
4	2880	114	2880	110	3260	105	3890	111	4150	101	3480	103	....	...	....	...
7	2510	99	2710	103	2880	93	3380	97	3750	91	3380	100	....	...	....	...
10	2640	104	2580	98	3030	98	3310	95	3710	90	2946	87	....	...	....	...
Average	2650	105	2770	105	3220	104	3570	102	3980	97	3400	101	....	...	....	...
6-month Tests																
0	2490	100	2560	100	3060	100	3660	100	3860	100	4520	100	4110	100	....	...
1	2570	103	2880	113	3230	106	3690	101	3960	103	4520	100	3920	95	....	...
2	2750	110	3130	125	3630	115	3900	107	4330	112	4690	104	4240	103	....	...
4	2720	109	3110	123	3350	109	3810	104	4280	111	4760	105	4050	98	....	...
7	2520	101	2760	109	2750	90	3300	90	3580	93	4240	94	3850	94	....	...
10	2110	85	2410	95	2590	88	2850	78	3450	89	4050	90	3380	82	....	...
Average	2530	110	2800	101	3080	101	3530	97	3910	101	4460	99	3930	95	....	...
1-year Tests																
0	3420	100	2790	100	3110	100	3140	100	4050	100	4370	100	4990	100	4790	100
1	2540	74	2800	100	3040	98	3650	116	3910	96	4440	102	5060	101	4590	96
2	2610	76	2980	107	3230	104	3880	123	4340	107	4370	100	4910	99	4520	94
4	2410	70	3400	122	3440	111	3930	125	4030	100	4510	103	5160	103	4080	85
7	2830	83	2800	100	3100	100	3370	107	3650	90	4000	91	4910	99	4320	90
10	2420	71	2460	88	2810	90	3460	110	3770	93	4200	96	4260	85	3800	79
Average	2700	79	2870	103	3120	101	3570	114	3960	99	4320	98	4880	98	4350	91
2½-year Tests																
0	2540	100	2560	100	3180	100	3360	100	3900	100	4190	100	5270	100	4980	100
1	2760	109	2790	109	3500	110	3550	106	3850	99	4150	99	4730	90	4840	97
2	2860	113	3350	131	3550	112	3680	110	3800	97	4360	104	5110	97	5620	113
4	3050	120	3140	123	3460	109	3460	103	3980	102	4420	106	4940	94	5730	115
7	2780	109	2850	111	2980	94	3160	94	3540	91	3870	92	4380	83	4880	98
10	2610	103	2760	108	3030	95	2970	88	3420	88	3560	85	4170	79	4340	87
Average	2770	109	2910	114	3280	103	3360	100	3750	96	4090	98	4770	91	5060	102

TABLE VII.—EFFECT OF CALCIUM CHLORIDE ON THE STRENGTH OF CONCRETE AND MORTAR AS INFLUENCED BY BRAND OF CEMENT—SERIES 156.

Compression tests of 6 by 12-in. concrete cylinders and 2 by 4-in. mortar cylinders.
Mix 1:5.2 by volume for concrete; 1:2.5 by volume for mortar.
Aggregate: sand and pebbles from Elgin, Ill.; sand graded 0 to No. 4 and sand and pebbles graded 0 to 1½ in.
Cement: 4 brands of portland cement "A," "B" "C" and "D" purchased in Chicago.
Relative consistency 1.00 (Flow about 180 for concrete and 130 for mortar, see Table XII).
Concrete specimens cured in moist room and mortar specimens in water until test; tested damp.
Each value for concrete strength is the average of 9 tests made on different days and for mortar 5 tests unless otherwise noted.
Strength-ratios are percentages of strength of concrete at same age without calcium chloride.
Calcium chloride and chlorine expressed in terms of weight of cement.
Data plotted in Fig. 11. Compare Table VIII.

Age at Test	Calcium Chloride *B*, per cent	Chlorine, per cent	Cement A		Cement B		Cement C		Cement D		Average Strength-Ratio, per cent
			Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	
COMPRESSION TESTS OF 6 BY 12-IN. CONCRETE CYLINDERS											
2 days	0	0	950[a]	100	750	100	570	100	740	100	100
"	4	1.9	1400[b]	147	810	108	810	142	1130	153	138
7 days	0	0	1940[a]	100	1640	100	1240	100	1620	100	100
"	4	1.9	2220[b]	114	1620	99	1530	123	2130	131	117
28 days	0	0	3310[a]	100	2990	100	2150	100	2650	100	100
"	4	1.9	3620[b]	109	2870	96	2520	117	3170	119	110
3 months	0	0	4170[a]	100	4220	100	3030	100	3860	100	100
"	4	1.9	4556[b]	109	4230	100	3450	114	4000	104	107
1 year	0	0	4320[a]	100	4580	100	3410	100	3890	100	100
"	4	1.9	5130[b]	119	4960	108	3870	113	4490	115	114
3 years	0	0	5020[a]	100	5480	100	4100	100	4840	100	100
"	4	1.9	5840[b]	116	5830	106	4430	108	4880	101	108
COMPRESSION TESTS OF 2 BY 4-IN. MORTAR CYLINDERS											
2 days	0	0	1970[c]	100	1840	100	1550	100	1450	100	100
"	4	1.9	2290	116	1490	81	1850	119	2330	161	119
7 days	0	0	3610[c]	100	3190	100	3190	100	3270	100	100
"	4	1.9	3640	101	2680	84	3420	107	4240	130	106
28 days	0	0	5100[c]	100	4710	100	4670	100	4740	100	100
"	4	1.9	4570	90	4760	101	4550	98	5900	125	103
3 months	0	0	6080[c]	100	5440	100	5500	100	5980	100	100
"	4	1.9	5180	85	6230	114	6290	114	6310	105	104
1 year	0	0	6520[c]	100	6060	100	6710	100	6520	100	100
"	4	1.9	5300	81	7280	120	7320	109	8070	124	108
3 years	0	0	6820[c]	100	7030	100	6920	100	7100	100	100
"	4	1.9	5590	82	7550	107	7200	104	7990	112	101

[a] Average of 25 tests.
[b] Average of 10 tests.
[c] Average of 15 tests.

Table VIII.—Effect of Calcium Chloride on the Strength of Concrete as Influenced by Brand of Cement—Series 158.

Compression tests of 6 by 12-in. concrete cylinders.
Mix 1:5.2 by volume (1:2:4).
Aggregate: sand and pebbles from Elgin, Ill., graded 0 to 1½ in.
Cement: 4 brands of portland cement "A," "B," "C" and "D" purchased in Chicago.
Relative consistency 1.00 (Flow about 180, see Table XII).
Specimens cured in moist room for 14 days; remainder in air.
Each value is the average of 5 tests made on different days.
Strength-ratios are percentages of strength of concrete at same age without calcium chloride.
Calcium chloride expressed in terms of weight of cement.
Compare Table VII.

Calcium Chloride *B*, per cent	Laboratory Cement[a]		Cement A		Cement B		Cement C		Cement D	
	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Compressive Strength lb. per sq. in.	Strength-Ratio, per cent
28-day Tests										
0	2650	100	2830	100	2500	100	2470	100	2170	100
1	2830	107	2660	94	2840	114	2610	106	2290	105
2	3200	121	2770	98	2600	104	2850	115	2460	113
4	3100	117	2630	93	2620	105	2950	119	2720	125
7	3000	113	3030	107	3140	126	2690	109	2660	123
10	2770	104	2810	99	2940	118	2770	112	2720	125
Average	2920	110	2790	99	2770	111	2720	110	2500	115
3-month Tests										
0	3500	100	3610	100	3290	100	3330	100	3070	100
1	3670	105	3250	90	3550	108	3110	93	2910	95
2	3670	105	3490	97	3680	112	3610	108	2880	94
4	3890	111	3340	92	3930	119	3820	114	3220	105
7	3380	97	3560	99	3390	103	3180	96	3190	104
10	3310	95	3630	101	3200	97	3220	97	2900	94
Average	3570	102	3480	96	3510	106	3380	101	3030	99
6-month Tests										
0	3660	100	3430	100	3100	100	3340	100	2840	100
1	3690	101	3590	105	3520	114	3390	102	2890	104
2	3900	107	3520	103	3550	115	3920	117	3060	108
4	3810	104	3450	101	3660	118	3590	107	2730	96
7	3300	90	3610	105	3470	112	3170	95	2650	93
10	2850	78	3380	99	2930	95	2810	84	3040	107
Average	3530	97	3500	102	3370	109	3370	101	2870	101
1-year Tests										
0	3140	100	3660	100	3340	100	3500	100	2870	100
1	3650	116	3420	93	3630	109	3530	101	2900	101
2	3880	124	3570	98	3790	114	3640	104	3040	106
4	3930	125	3430	94	3630	109	3590	103	3090	108
7	3370	107	3940	108	3440	103	3290	94	2820	98
10	3460	110	3300	90	3270	98	2980	85	2700	94
Average	3570	114	3550	97	3520	106	3420	98	2900	101
2½-year Tests										
0	3360	100	3430	100	3370	100	3390	100	2860	100
1	3550	106	3770	110	3320	99	3660	108	2850	100
2	3680	110	3770	110	3600	107	3630	107	3040	106
4	3460	103	3310	96	3560	106	3580	106	3080	108
7	3160	94	3450	101	3150	93	3120	92	3470	121
10	2970	88	3380	99	3100	92	2930	86	2700	94
Average	3360	100	3520	103	3350	100	3380	100	3000	105

[a] A mixture of the four brands, A, B, C and D, given above, but not of the same lot; same cement used for tests in Table VI. The individual brands are the same as those in Series 156, but not the same lots.

TABLE IX.—EARLY STRENGTH OF CONCRETE CURED AT LOW TEMPERATURES—SERIES 188.

Compression tests of 6 by 12-in. cylinders.
Mix: 1:5 by volume.
Aggregate: sand and pebbles from Elgin, Ill., graded 0 to 1½ in. (fineness modulus, 5.65).
Cement: a mixture of four brands purchased in Chicago.
Relative consistency 1.25. (Slump about 8 in. Flow test not made.)
Outdoor temperatures ranged from 24 to 37° F. The aggregate, cement and water were stored outdoors in covered metal cans 18 to 20 hours before use.
Specimens cured outdoors were kept under wet burlap for 14 days; remainder in air; laboratory cured cylinders were placed in moist room on the day molded.
Calcium chloride expressed in terms of weight of cement.
Strength-ratios are percentages of the strength of concrete specimens made and cured in laboratory under standard conditions.
Each value is the average of 6 tests made on different days.
Data plotted in Fig. 16

Place Made	Place Cured	Temperature, deg. Fahr.		Calcium Chloride, per cent	Temperature of Concrete after Molding, deg. Fahr.								1 day		2 days		4 days		7 days		14 days		28 days		3 months	
		Cement and Aggregate	Mixing Water		0 min.	15 min.	30 min.	1 hr.	2 hr.	3 hr.	4 hr.	20 hr.	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent
Laboratory	Laboratory	66	63	0	64	66	64	64	64	63	64	64	150	100	410	100	830	100	1230	100	1880	100	2640	100	4620	100
Laboratory	Outdoors	66	63	0	64	66	64	64	63	59	57	36	65	43	100	24	160	19	430	35	1020	54	1670	63	2930	63
Laboratory	Laboratory	66	66	3	66	68	68	66	64	61	61	66	260	173	600	146	950	114	1260	102	1790	95	2320	88	3670	79
Laboratory	Outdoors	66	66	3	66	66	66	66	64	61	61	36	75	50	200	49	460	55	750	61	1130	60	1820	69	2670	58
Outdoors	Outdoors	37	36	0	37	37	39	37	37	37	39	36	15	10	45	11	120	14	300	24	850	45	1660	63	2820	61
Outdoors	Laboratory	37	36	0	37	37	37	37	36	36	37	64	45	30	180	44	560	67	960	78	1570	84	2680	101	4410	95
Outdoors	Outdoors	37	39	3	39	39	39	39	39	41	41	36	50	33	185	45	415	50	710	58	1120	60	1980	75	2900	63
Outdoors	Laboratory	37	39	3	39	39	39	39	37	37	39	64	160	107	380	93	670	81	1010	82	1640	87	2160	82	3440	74
Outdoors	Outdoors	37	66	0	45	43	43	41	39	41	39	36	15	10	60	15	160	19	420	34	950	50	1690	64	2740	59
Outdoors	Outdoors	37	124	0	59	52	50	46	61	59	37	34	15	10	65	16	180	22	470	38	1060	56	1850	70	2890	63
Outdoors	Outdoors	37	199	0	73	64	61	54	46	63	61	34	15	10	80	20	220	27	490	40	1200	64	1930	73	3120	68
Outdoors	Outdoors	59	36	0	54	50	48	45	41	39	39	33	15	10	60	15	140	17	385	31	1070	57	2030	77	2960	64
Outdoors	Outdoors	57	66	0	59	55	54	66	63	63	41	34	20	13	55	13	150	18	410	33	1180	63	2040	77	3400	74
Outdoors	Outdoors	61	124	0	70	64	59	55	52	46	45	36	20	13	80	20	185	22	465	38	1230	65	1920	73	2970	64
Outdoors	Outdoors	63	203	0	88	77	75	64	57	50	48	36	20	13	80	20	200	24	520	42	1150	61	1890	72	2880	62

TABLE X.—MAXIMUM STRENGTH-RATIOS FOR CONCRETE AND MORTAR USING CHEMICAL ADMIXTURES—SERIES 156.

Based on data in Tables I and II and Fig. 1.
Mix for concrete, 1:5.2; for mortar, 1:2.5 by volume.
Relative consistency 1.00.

Chemical Admixture	Calcium Chloride Content, per cent by Weight	Maximum Strength-Ratio[a]						Percentage of Admixture at which Maximum Strength Occurs					
		2 days	7 days	28 days	3 months	1 year	3 years	2 days	7 days	28 days	3 months	1 year	3 years
6 BY 12-IN. CONCRETE CYLINDERS													
None	0	950[c]	1940[c]	3310[c]	4170[c]	4320[c]	5020[c]	...	...	...	...	...	...
Calcium Chloride, *A*	74	170	125	110	112	117	118	4 1.9[b]	3 1.5	3 1.5	3 1.5	4 1.9	4 1.9
Calcium Chloride, *B*	75	147	124	109	109	119	116	4 1.9[b]	2 1.0	4 1.9	4 1.9	4 1.9	4 1.9
Cal (standard chlorine)	25	151	123	107	107	121	119	7 1.1[b]	7 1.1	7 1.1	10 1.6	10 1.6	7 1.1
Cal (low chlorine)	17	143	118	101	104	113	111	10 1.1[b]	10 1.1	7 0.7	10 1.1	10 1.1	15 1.6
Vitriflux	34	138	115	106	108	109	114	7 1.5[b]	7 1.5	6 1.3	7 1.5	4 0.9	7 1.5
Magnesium chloride	46 ($MgCl_2$)	115	Decrease for all percentages					1 0.3[b]	0 0	0 0	0 0	0 0	0 0
2 BY 4-IN. MORTAR CYLINDERS (0 TO NO. 4 ELGIN SAND)													
None	0	1970[d]	3610[d]	5100[d]	6080[d]	6520[d]	6820[d]	...	...	...	...	...	...
Calcium chloride, *A*	74	146	120	109	107	106	106	2 1.0[b]	2 1.0	2 1.0	2 1.0	2 1.0	1 0.5
Calcium chloride, *B*	75	130	110	{ Decrease for all percentages }				2 1.0[b]	2 1.0	0 0	0 0	0 0	0 0
Cal (standard chlorine)	25	162	136	122	122	121	130	7 1.1[b]	7 1.1	7 1.1	7 1.1	7 1.1	7 1.1
Cal (low chlorine)	17	139	124	107	107	107	100	10 1.1[b]	10 1.1	7 0.7	7 0.7	10 1.1	10 1.1
Vitriflux	34	148	128	114	108	108	103	4 0.9[b]	4 0.9	4 0.9	4 0.9	4 0.9	1 0.2
Magnesium chloride	46 ($MgCl_2$)	131	112	106	110	110	110	2 0.7[b]	2 0.7	4 1.4	2 0.7	2 0.7	1 0.3

[a] Percentage of strength of similar concrete or mortar at given age without admixture.
[b] Percentage of chlorine based on weight of cement.
[c] Strength of concrete without admixture, lb. per sq. in.
[d] Strength of mortar without admixture, lb. per sq. in.

TABLE XI.—SUMMARY OF TESTS ON CALCIUM CHLORIDE IN CONCRETE.

Item	Compressive Strength Without Admixture, lb. per sq. in.						Maximum Strength-Ratio Using Calcium Chloride						Per cent Calcium Chloride Giving Maximum Strength					
	2 days	7 days	28 days	3 mo.	1 year	3 years	2 days	7 days	28 days	3 mo.	1 year	3 years	2 days	7 days	28 days	3 mo.	1 year	3 years
EFFECT OF MIX—SERIES 156—RELATIVE CONSISTENCY 1.00; CEMENT A; SEE TABLE III AND FIG. 3																		
Mix 1:7	540	1100	2060	2790	3050	3500	120	106	[a]	[a]	[a]	[a]	4	2	0	0	0	0
Mix 1:5.2	950	1940	3310	4170	4320	5020	147	124	109	109	119	116	4	2	4	4	4	4
Mix 1:4	1350	2660	4240	5140	5750	6390	149	130	116	112	110	113	2	2	2	2	2	2
Mix 1:3	1960	3680	4920	5960	6490	7530	159	130	128	118	113	116	2	2	4	2	4	2
Mix 1:2	2780	4530	5750	6140	7090	8390	149	130	123	131	107	107	2	2	2	4	4	2
EFFECT OF CONSISTENCY—SERIES 156—MIX 1:5.2; CEMENT A; SEE TABLE IV AND FIG. 5																		
Rel. Consist. 0.90	1110	2370	3830	4590	4450	5170	153	116	100	104	126	116	2	2	4	4	2	4
" " 1.00	950	1940	3310	4170	4320	5020	147	124	109	109	119	116	4	2	4	4	4	4
" " 1.10	720	1560	2750	3830	4030	4480	144	115	101	101	105	111	2	2	4	2	4	4
" " 1.25	440	1070	2100	2840	3060	3460	159	117	[a]	[a]	[a]	102	2	2	0	0	0	2
" " 1.50	280	640	1200	1860	2080	2400	146	122	107	[a]	104	[a]	2	2	2	0	10	0
EFFECT OF CURING CONDITION—SERIES 156—MIX 1:5.2; RELATIVE CONSISTENCY 1.00; CEMENT A; SEE TABLE V AND FIGS. 7 AND 8																		
Moist Room	....	....	3310	4170	4320	5020	...	...	109	109	119	116	..	..	4	4	4	4
Water Curing	....	....	3140	4080	4520	4720	...	...	110	106	108	111	..	..	2	2	2	7
Air Curing	....	....	2600	2950	2660	2990	...	...	122	121	123	123	..	..	4	2	2	2
EFFECT OF CURING CONDITION—SERIES 158—MIX 1:5.2; RELATIVE CONSISTENCY 1.00; CEMENT, 4 BRANDS; SEE TABLE VI AND FIGS. 9 AND 10																		
Moist Room, 0 days[c]	....	1340	2080	2530	3420	2540	...	134	119	114	[a]	120	..	4	4	4	0	4
" " 3 days[c]	....	1450	2220	2630	2790	2560	...	126	122	121	122	131	..	2	4	2	4	2
" " 7 days[c]	....	1310	2720	3110	3110	3180	...	123	112	116	111	112	..	2	4	2	4	2
" " 14 days[c]	....	....	2660	3500	3140	3360	...	...	121	111	125	110	..	..	2	4	4	2
" " 28 days[c]	....	....	2640	4120	4050	3900	...	...	106	101	107	102	..	..	2	4	2	4
" " 3 mo.[c]	....	....	....	3380	4370	4190	...	...	...	108	103	106	..	..	..	2	4	4
" " 6 mo.[c]	....	....	....	....	4990	5270	...	...	...	...	103	[a]	..	..	..	..	4	0
" " 1 year[c]	....	....	....	....	4790	4980	...	...	...	...	[a]	115	..	..	..	..	0	4
EFFECT OF BRAND OF CEMENT—SERIES 156—MIX 1:5.2; RELATIVE CONSISTENCY 1.00; SEE TABLE VII AND FIG. 11																		
Cement A	950	1940	3310	4170	4320	5020	147	114	109	109	119	116	Tests made for 4 per cent calcium chloride only					
" B	750	1640	2990	4220	4580	5480	108	[a]	[a]	[a]	108	106						
" C	570	1240	2150	3030	3410	4100	142	123	117	114	113	108						
" D	740	1620	2650	3860	3890	4840	153	131	119	104	115	101						
EFFECT OF BRAND OF CEMENT[b]—SERIES 158—MIX 1:5.2; RELATIVE CONSISTENCY 1.00; SEE TABLE VIII																		
Cement, Lab.	....	....	2650	3500	3140	3360	...	...	121	111	125	110	..	..	2	4	4	2
" A	....	....	2830	3610	3660	3430	...	...	107	101	108	110	..	..	7	10	7	1
" B	....	....	2500	3290	3340	3370	...	...	126	119	114	107	..	..	7	4	2	2
" C	....	....	2470	3330	3500	3390	...	...	119	114	104	108	..	..	4	4	2	1
" D	....	....	2170	3070	2870	2860	...	..	125	105	108	121	..	..	4	4	4	1

[a] Decrease in strength with all percentages of calcium chloride
[b] Cured 14 days in moist room; remainder in dry air.
[c] Remainder in air of laboratory.

TABLE XII.—WATER-RATIOS AND FLOW TESTS—SERIES 156.

Water is expressed as the ratio of volume of water to volume of cement.

Plasticity of the concrete and mortar was measured by means of the flow table. The apparatus consists of a truncated cone and a table mounted on a cam in such a way that it can be raised and dropped ½ inch For concrete, a truncated cone 6⅔ by 10 by 5 in. was used with a table 25½ in. in diameter. For the mortar tests the truncated cone was 4 by 6 by 3 in. and the table 17 in. in diameter. The concrete or mortar to be tested was molded in the cone on the table. Immediately after filling, the cone was withdrawn and the table dropped 15 times in about 10 seconds. The base diameter of the concrete was measured and this diameter expressed as a percentage of the base diameter of the cone is the "flow".

Five to ten specimens were made in each set on different days. The flow was determined only for the first specimen in a set. The same quantity of mixing water was used throughout the set.

Admixture expressed as per cent of weight of cement.

A. CONCRETE AND MORTAR TESTS; TABLES I AND II

Admixture, per cent	Calcium Chloride *A*		Calcium Chloride *B*		Cal				Vitriflux		Magnesium Chloride	
					Standard		Low Chlorine					
	Water-Ratio	Flow	Water-Ratio	Flow	Water-Ratio	Flow	Water-Ratio	Flow	Water-Ratio	Flow	Water-Ratio	Flow
1:5.2 CONCRETE; SEE TABLE I												
0[c]	0.85	173	0.85	173	0.85	173	0.85	173	0.85	173	0.85	173
1	0.85	180[a]	0.85	172	....	....	....	....	0.85	177	0.89	185
2	0.83	180[a]	0.84	169	0.86	180	0.86	172	0.85	181	0.91	185
4	0.80	176[a]	0.80	160	0.86	187	0.86	176	0.85	177	0.93	190
7	0.84	177[a]	0.84	169	0.86	179	0.86	176	0.85	185	0.91	181
10	0.83	163[a,b]	0.84	160[e]	0.86	176	0.88	171	0.85	186	0.94	178
15	....	...	....	...	0.88	185	0.88	171	0.85	181	....	...
20	....	...	....	...	0.90	190	0.90	172	....	...	....	...
1:2½ MORTAR; SEE TABLE II												
0[d]	0.58	125	0.58	125	0.58	125	0.58	125	0.58	125	0.58	125
1	0.58	123	0.56	118	....	...	....	...	0.57	122	0.64	135
2	0.62	119	0.58	116	0.60	131	0.60	133	0.59	126	0.70	144
4	0.69	126	0.58	122	0.61	138	0.61	132	0.61	128	0.78	141
7	....	...	....	...	0.61	140	0.61	132	0.63	123	0.93	143
10	....	...	....	...	0.62	146	0.62	143	0.65	120	....	...
15	....	...	....	...	0.62	146	0.62	136	....	...	....	...
20	....	...	....	...	0.63	152	0.63	133	....	...	....	...

[a] Average of 8 tests.
[b] Values for flow erratic due to quick stiffening. Omitting three sets of low values, the average becomes 179.
[c] Average of 25 tests.
[d] Average of 15 tests.
[e] Values of flow erratic due to quick stiffening.

TABLE XII—*Continued.*

B. CONCRETE TESTS; SEE TABLE III

Calcium Chloride *B*, per cent	Mix by Volume									
	1:7		1:5		1:4		1:3		1:2	
	Water-Ratio	Flow	Water-Ratio	Flow	Water-Ratio	Flow	Water-Ratio	Flow	Water-Ratio	Flow
0	1.09	166	0.85	173	0.73	174	0.58	172	0.49	170
1	1.11	180	0.85	172	0.73	175	0 60	168	0.49	166
2	1.14	179	0.84	169	0.71	177	0.58	137	0.48	168
4	1.10	178	0.80	160	0.70	185	0.58	171	0.49	180
7	1.10	169	0.84	169	0.69	166	0.58	161	0.54	211
10	1.08	174	0.84	160	0.74	189	0.58	163	0.54	195

C. 1:5.2 CONCRETE; SEE TABLE IV

Calcium Chloride *B*, per cent	Relative Consistency									
	0.90		1.00		1.10		1.25		1.50	
	Water-Ratio	Flow	Water-Ratio	Flow	Water-Ratio	Flow	Water-Ratio	Flow[f]	Water-Ratio	Flow[f]
0	0.76	152	0.85	173	0.94	200	1.06	...	1.28	...
1	0.76	154	0.85	172	0.94	202	1.07	...	1.29	...
2	0.76	150	0.84	169	0.94	210	1.06	...	1.28	...
4	0.76	151	0.80	160	0.94	205	1.07	...	1.28	...
7	0.76	160	0.84	169	0.94	196	1.07	...	1.28	...
10	0.76	157	0.84	160	0.94	208	1.06	...	1.28	...

D. 1:5.2 CONCRETE; SEE TABLE V

Calcium Chloride *B*, per cent	Moist Room Curing		Water Curing		Air Curing	
	Water-Ratio	Flow	Water-Ratio	Flow	Water-Ratio	Flow
0	0.85	173	0.85	175	0.85	180
1	0.85	172	0.85	174	0.85	180
2	0.84	169	0.85	180	0.85	184
4	0.80	160	0.85	179	0.85	184
7	0.84	169	0.85	184	0.85	183
10	0.84	160	0.83	177	0.83	170

E. CONCRETE AND MORTAR TESTS WITH DIFFERENT CEMENTS; TABLE VII

Calcium Chloride *B*, per cent	Cement A		Cement B		Cement C		Cement D	
	Water-Ratio	Flow	Water-Ratio	Flow	Water-Ratio	Flow	Water-Ratio	Flow
1:5.2 CONCRETE; SEE TABLE VII								
0	0.85	173	0.85	164	0.85	157	0.85	163
4	0.80	160	0.85	163	0.85	155	0.85	167
1:2½ MORTAR; SEE TABLE VII								
0	0.58	125	0.59	133	0.63	139	0.62	132
4	0.58	122	0.82	161	0.77	137	0.75	139

[f] Over limit of flow table.

TABLE XIII.—TESTS OF CEMENTS.

MISCELLANEOUS TESTS

Tests made in accordance with the Standard Specifications and Tests for Portland Cement of the American Society for Testing Materials.
Each value is the average of 2 to 4 tests.

Series	Cement	Residue on No. 200 Sieve	Water for Normal Consistency, per cent by Weight	Time of Setting				Soundness Test (over boiling water)
				Vicat Needle				
				Initial		Final		
				hr.	min.	hr.	min.	
156..	A	17.6	23.0	1	30	3	35	O.K.
	B	19.8	24.5	2	45	5	00	O.K.
	C	21.0	24.0	2	50	6	05	O.K.
	D	11.6	24.0	2	40	5	25	O.K.
158....	Laboratory	17.4	23.5	3	40	7	50	O.K.
188....	Laboratory	18.4	23.5	3	40	6	50	O.K.

Series	Cement	Time of Setting				Soundness Test (over boiling water)
		Gillmore Needle				
		Initial		Final		
		hr.	min.	hr.	min.	
156..	A	2	15	5	30	O.K.
	B	3	50	6	20	O.K.
	C	4	10	7	05	O.K.
	D	4	10	6	55	O.K.
158....	Laboratory	6	20	8	55	O.K.
188....	Laboratory	5	25	7	55	O.K.

STRENGTH TESTS

1:3 standard sand mortar.
Tests made in accordance with the Standard Specifications and Tests for Portland Cement of the American Society for Testing Materials.
Specimens cured in water; tested damp.
Each value is the average of 5 to 10 tests made on different days.

Series	Cement	Mixing Water, per cent	Tensile Strength of Briquettes, lb. per sq. in.					Compressive Strength of 2 by 4-in Cylinders, lb. per sq. in.				
			3 days	7 days	28 days	3 months	1 year	3 days	7 days	28 days	3 months	1 year
156..	A	10.3	220	250	360	375	400	960	1750	2890	3520	3650
	B	10.6	175	235	365	430	405	1020	1630	2930	3750	3280
	C	10.5	180	245	340	420	390	830	1450	2170	2850	3030
	D	10.5	185	265	375	415	385	1140	1710	3030	3690	3180
158....	Laboratory	10.5	...	270	390	430	440	....	1660	2520	3340	3890
188....	Laboratory	10.4	...	310	405	450	....	....	1820	2930	3950	....

TABLE XIV.—INFLUENCE OF ADMIXTURES ON TIME OF SETTING OF CEMENT—SERIES 156.

Tests for time of setting made with Cement A, only.

Admixture	Calcium Chloride, per cent	Chlorine Combined as Chloride, per cent	Admixture, per cent of weight of cement	Normal Consistency, per cent by weight	Time of Setting								Soundness Test (over boiling water)
					Vicat Needle				Gillmore Needle				
					Initial		Final		Initial		Final		
					hr.	min.	hr.	min.	hr.	min.	hr.	min.	
None	..	....	0	23.0	1	30	3	35	2	15	5	30	O.K.
Calcium chloride, *A*	74	47.5	1	22.0	1	20	3	05	2	10	3	15	O.K.
			2	23.0	1	20	2	25	2	00	3	10	O.K.
			4[a]	25.0	0	10	1	10	0	20	1	20	O.K.
Calcium chloride, *B*	75	48.0	1	22.0	1	10	2	30	2	00	3	05	O.K.
			2	23.0	1	00	2	10	1	30	2	40	O.K.
			4[a]	25.0	0	10	0	40	0	20	1	10	O.K.
Cal (low chlorine)	17	10.6	2	23.0	1	20	3	00	2	10	4	50	O.K.
			4	23.5	1	10	2	55	2	20	3	30	O.K.
			7	24.5	1	00	2	20	2	20	3	30	O.K.
			10	25.0	0	45	2	15	1	50	2	35	O.K.
			15	26.0	0	40	1	20	1	20	2	10	O.K.
			20	29.0	0	20	1	20	1	10	2	00	O.K.
Vitriflux	34	21.4	1	22.5	0	55	3	15	1	50	3	40	O.K.
			2	22.5	1	05	2	30	2	00	3	30	O.K.
			4	22.5	0	50	2	00	1	45	2	40	O.K.
			7	23.0	0	05	1	30	0	10	1	20	O.K.
			10	24.5	Flash Set								O.K.
Magnesium chloride	46[b]	34.4	1	22.5	1	20	3	10	2	35	3	50	O.K.
			2	23.0	1	20	6	10	2	30	3	50	O.K.
			4	24.5	1	10	2	40	2	05	3	15	O.K.
			7[a]	27.0	0	40	1	50	1	40	3	00	O.K.

[a] Higher percentages gave flash set.
[b] Magnesium chloride.

TABLE XV.—CHEMICAL ANALYSES OF CEMENTS.

Tests made in accordance with Standard Specifications and Tests for Portland Cement of the American Society for Testing Materials.
Values are the average of 2 tests expressed as percentages by weight.

Cement	Silica (SiO_2)	Iron and Aluminum Oxides (Fe_2O_3+ Al_2O_3)	Calcium Oxide (CaO)	Magnesium Oxide (MgO)	Sulfuric Anhydride (SO_3)	Loss on Ignition	Insoluble Residue
SERIES 156							
A	20.89	9.58	62.95	2.24	1.58	2.06	0.34
B	22.32	10.27	61.57	1.88	1.91	1.33	0.15
C	21.32	9.54	62.16	0.66	1.76	2.96	0.26
D	22.58	6.74	61.71	3.65	1.21	2.72	0.44
SERIES 158							
Laboratory	21.11	9.38	61.95	2.68	1.78	2.16	0.40
A	19.42	10.74	62.93	2.25	1.53	2.75	0.26
B	21.08	10.48	61.62	1.76	2.72	1.97	0.38
C	20.96	10.63	62.97	1.43	1.54	2.15	0.18
D	20.52	8.20	63.00	4.04	1.45	2.32	0.20
SERIES 188							
Laboratory	22.42	9.17	62.10	2.71	1.82	1.15	0.18

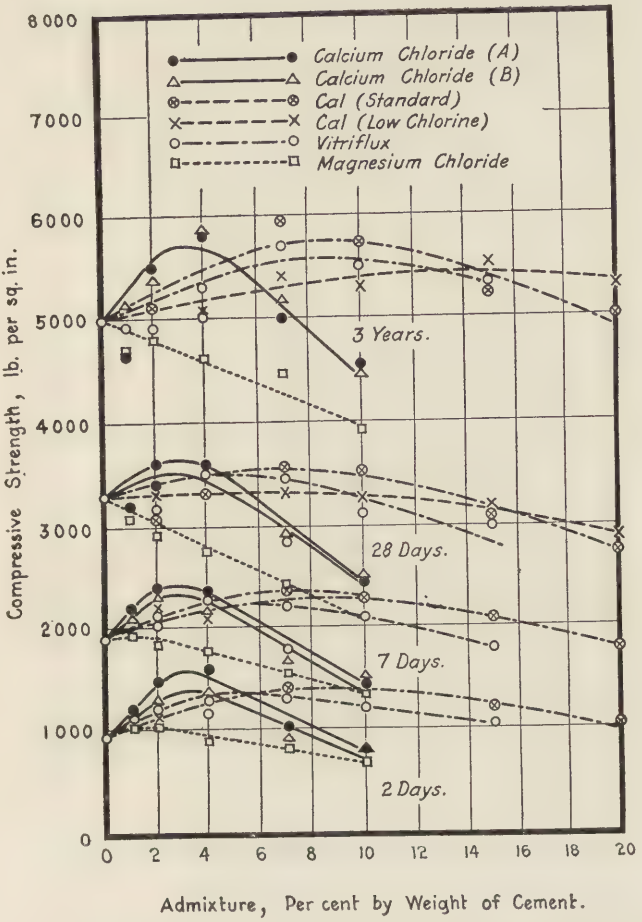


FIG. 1.—Effect of Type of Admixture on the Strength of Concrete.

Compression tests of 6 by 12-in. concrete cylinders cured in moist room.
Mix 1 : 5.2 by volume; relative consistency 1.00.
Each value is the average of from 4 to 10 tests made on different days.
Data from Table I; curves for 3 months and 1 year omitted.

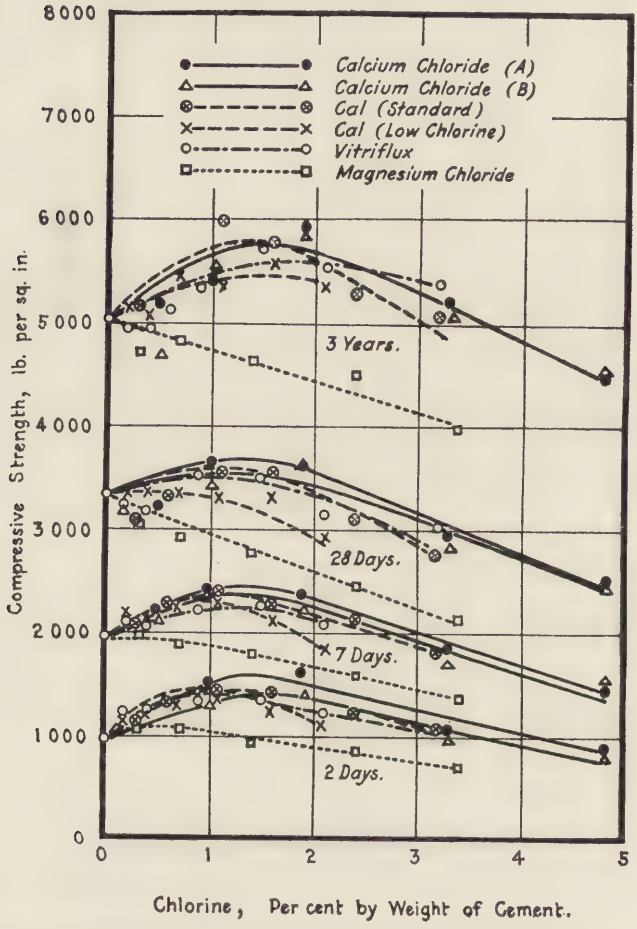


FIG. 2.—Effect of Type of Admixture on the Strength of Concrete

Same data as in Fig. 1, except admixture expressed in terms of chlorine content. Data from Table I; curves for 3 months and 1 year omitted.

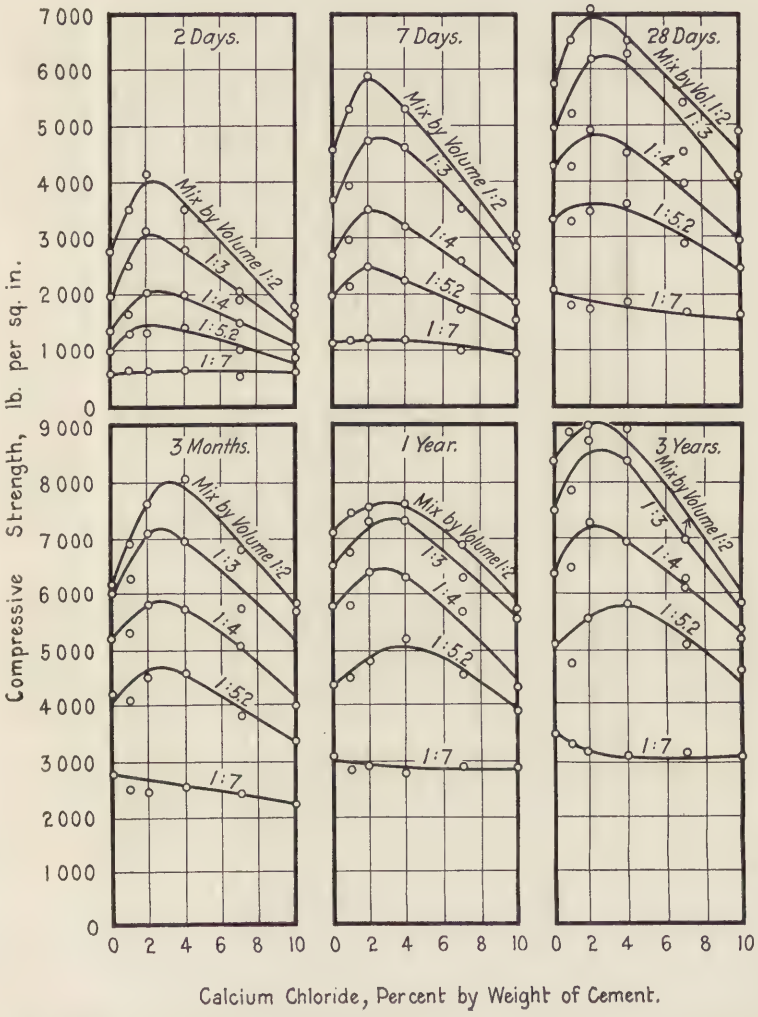


FIG. 3.—Effect of Calcium Chloride on the Strength of Concrete as Influenced by Mix.

Compression tests of 6 by 12-in. concrete cylinders cured in moist room.
Each value is the average of 5 tests made on different days.
Calcium chloride *B* was used.
Data from Table III.

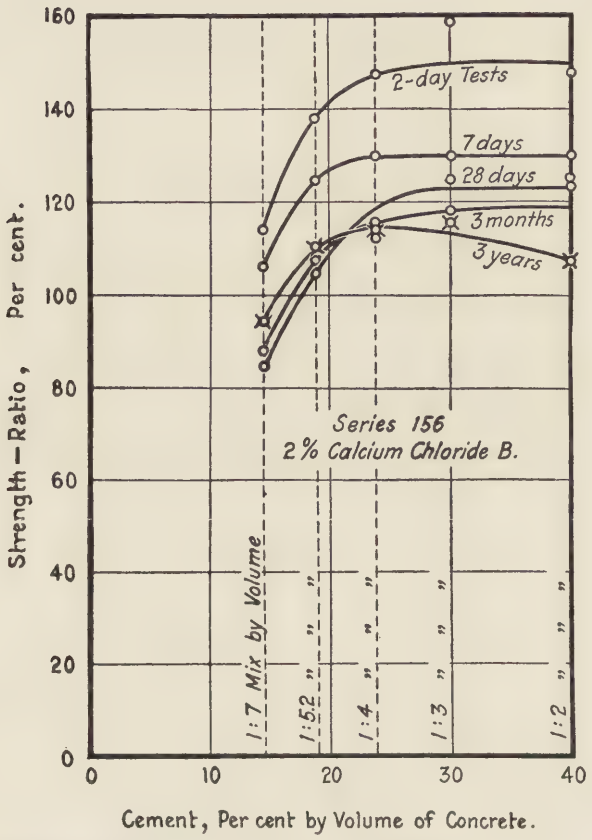


FIG. 4.—Effect of Calcium Chloride on the Strength of Concrete as Influenced by Mix.

Strength-ratios from Table III for 2 per cent calcium chloride *B*.
Same data used in Fig. 3.
Strength-ratios are percentages of strength of concrete at same age without calcium chloride.
Curve for 1 year omitted.

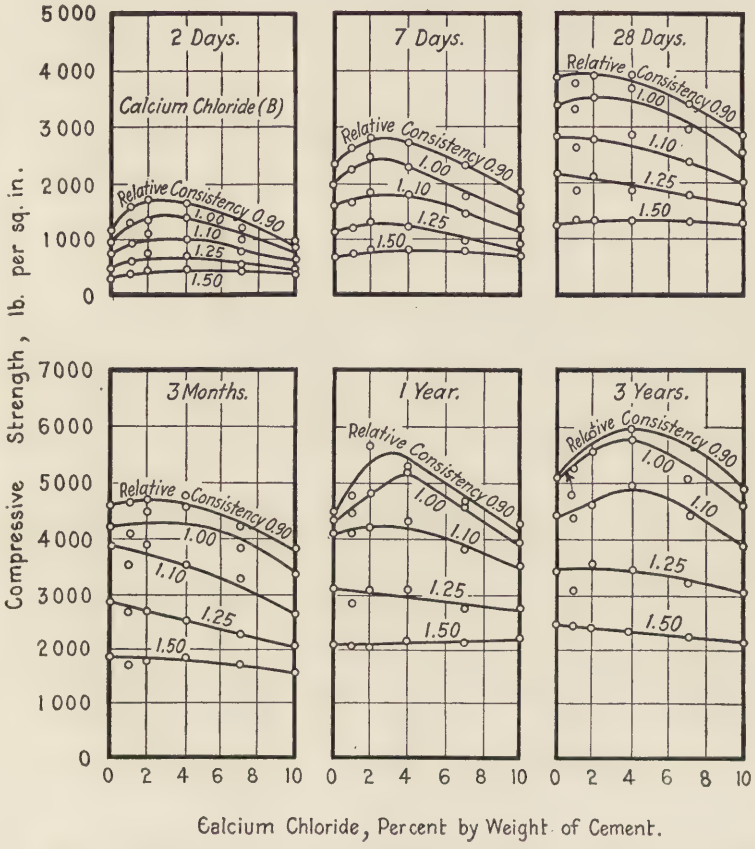


FIG. 5.—Effect of Calcium Chloride on the Strength of Concrete as Influenced by Consistency.

Compression tests of 6 by 12-in. concrete cylinders cured in moist room.
Mix 1: 5.2 by volume.
Each value is the average of 5 tests made on different days.
Data from Table IV.

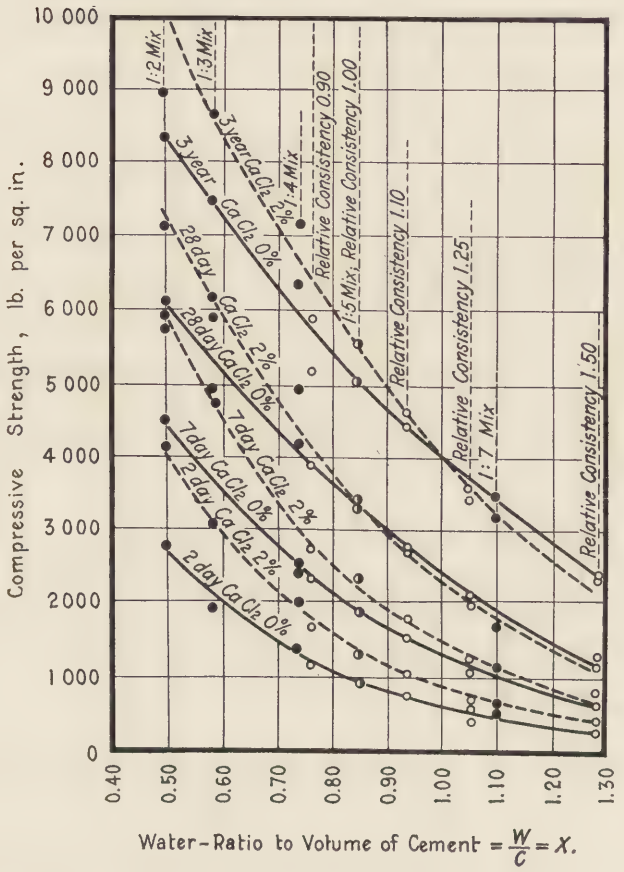


FIG. 6.—Water-Ratio-Strength Relation for Concrete.

Compression tests of 6 by 12-in. concrete cylinders cured in moist room.
Data plotted for "plain" concrete and concrete containing 2 per cent of calcium chloride *B*.
Data from Tables III, IV and XII.

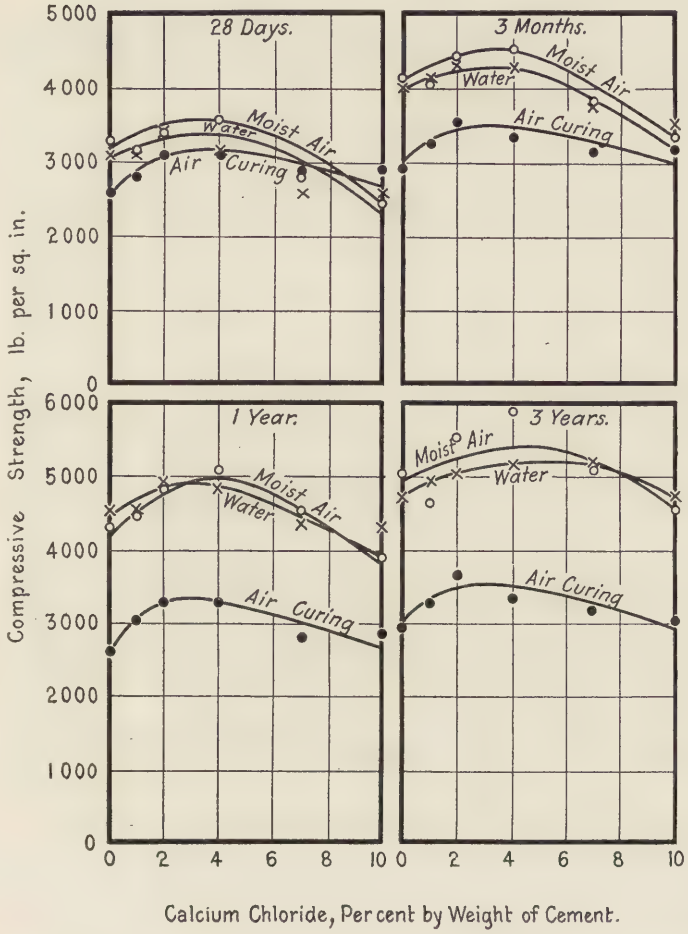


FIG. 7.—Effect of Calcium Chloride on the Strength of Concrete as Influenced by Condition of Curing.

Compression tests of 6 by 12-in. concrete cylinders.
Mix 1: 5.2 by volume; relative consistency 1.00.
In general, each value is the average of 9 tests made on different days.
Calcium chloride *B* was used.
Data from Table V.

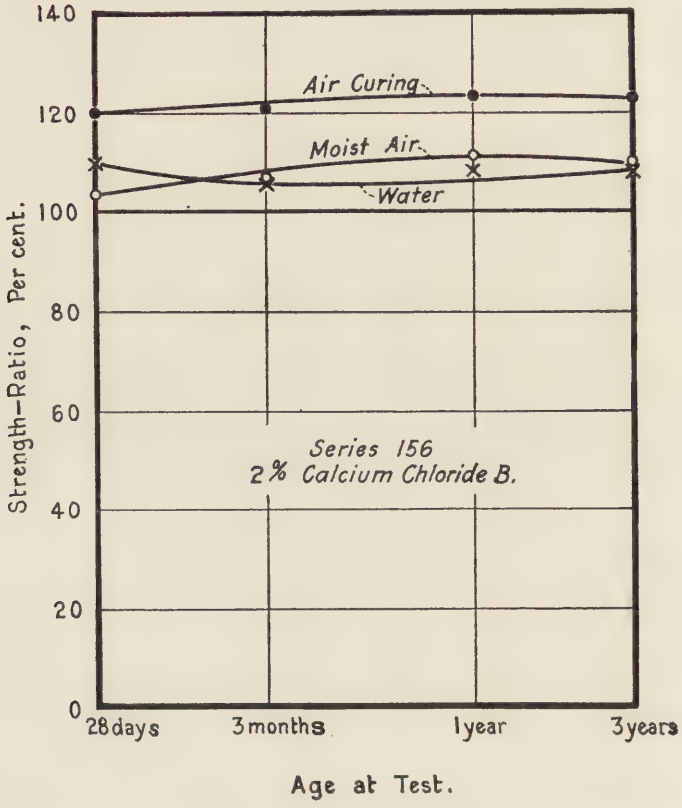


FIG. 8.—Effect of Calcium Chloride on the Strength of Concrete as Influenced by Condition of Curing

Age plotted to logarithmic scale.
Strength-ratios from Table V for 2 per cent calcium chloride *B*.
Same data used in Fig. 7.
Strength-ratios are percentages of strength of concrete at same age without calcium chloride.

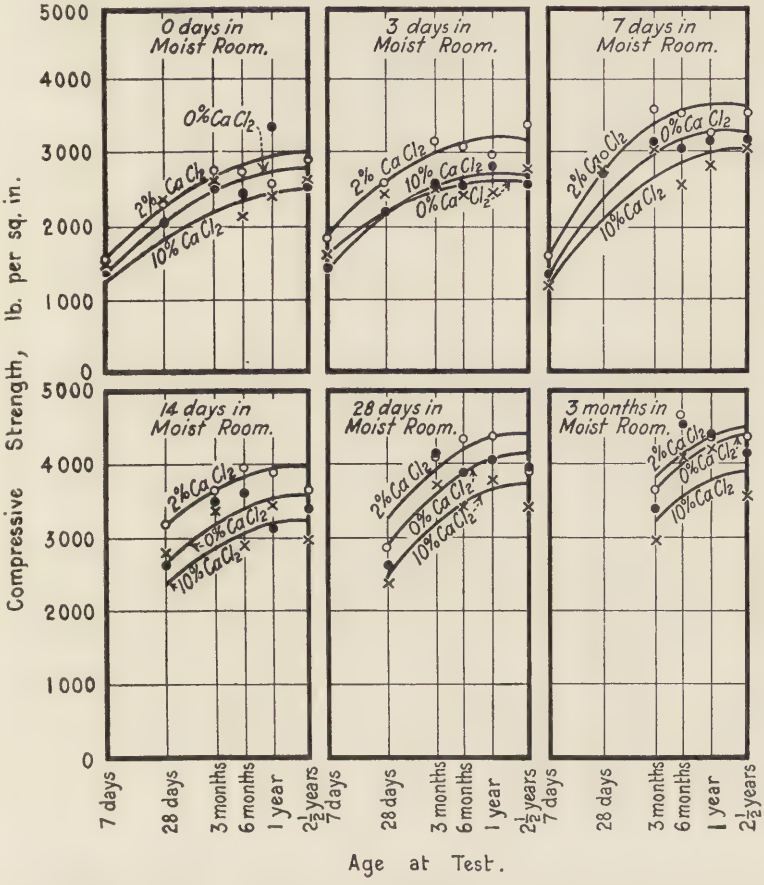


FIG. 9.—Effect of Calcium Chloride on the Strength of Concrete as Influenced by Condition of Curing.

Compression tests of 6 by 12-in. concrete cylinders cured in moist room for period indicated and remainder in air.
Age plotted to logarithmic scale.
Mix 1:5.2 by volume; relative consistency 1.00.
Each value is the average of 5 tests made on different days.
Calcium chloride *B* was used.
Data from Tab'e VI.

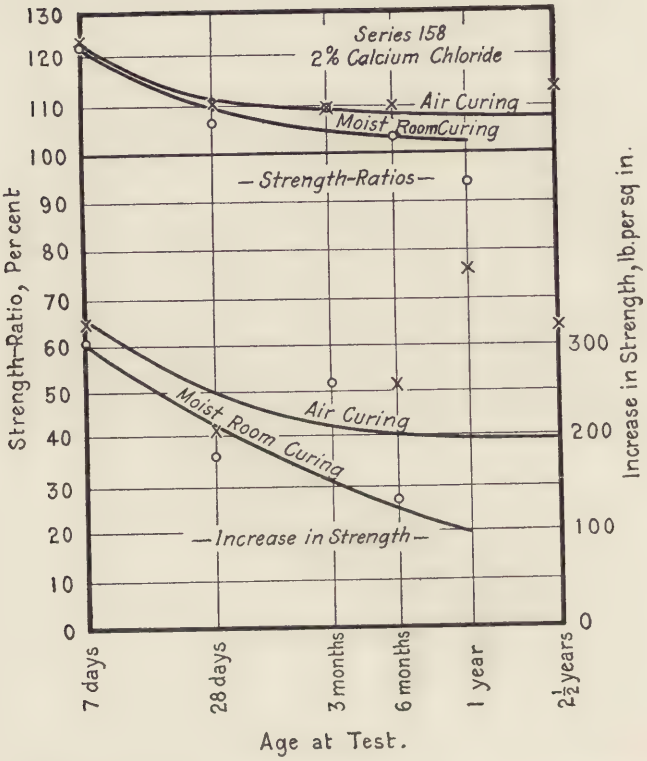


FIG. 10.—Effect of Calcium Chloride on the Strength of Concrete as Influenced by Condition of Curing.

Age plotted to logarithmic scale.
Same data used in Fig. 9.
Increase in strength shown for 2 per cent calcium chloride *B*.
Data from Table VI.

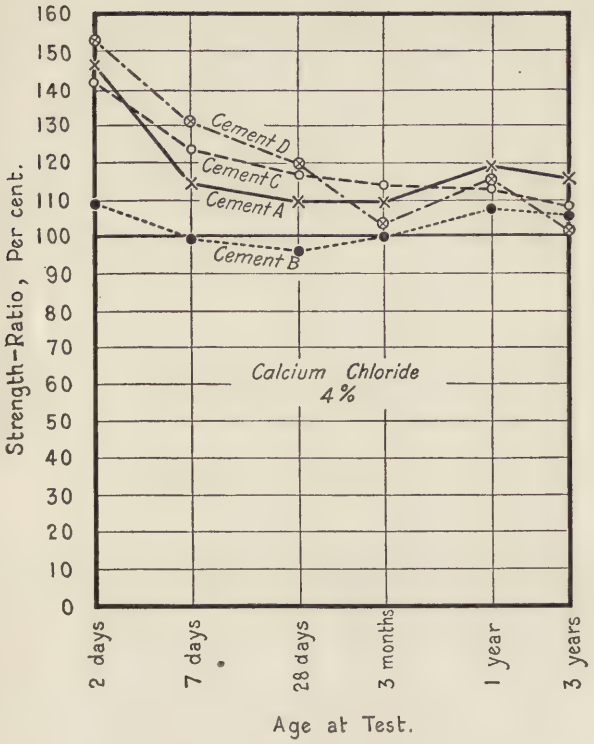


FIG. 11.—Effect of Calcium Chloride on the Strength of Concrete as Influenced by Brand of Cement.

Compression tests of 6 by 12-in. concrete cylinders cured in moist room.
Age plotted to logarithmic scale.
Mix 1:5.2 by volume; relative consistency 1.00.
Calcium chloride *B* was used.
Data from Table VII.

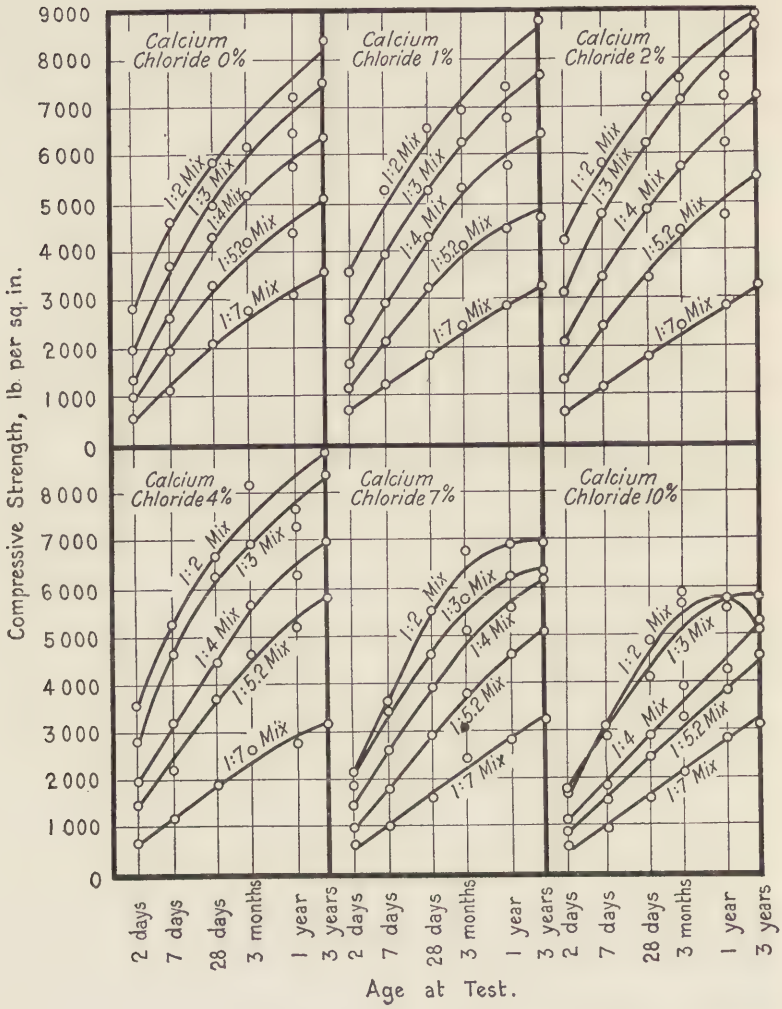


FIG. 12.—Effect of Age on the Strength of Concrete.

Compression tests of 6 by 12-in. concrete cylinders cured in moist room.
Age plotted to logarithmic scale.
Relative consistency 1.00.
Calcium chloride *B* was used.
Each value is the average of 5 tests made on different days.
Data from Table III; compare Figs. 13, 14, and 15.

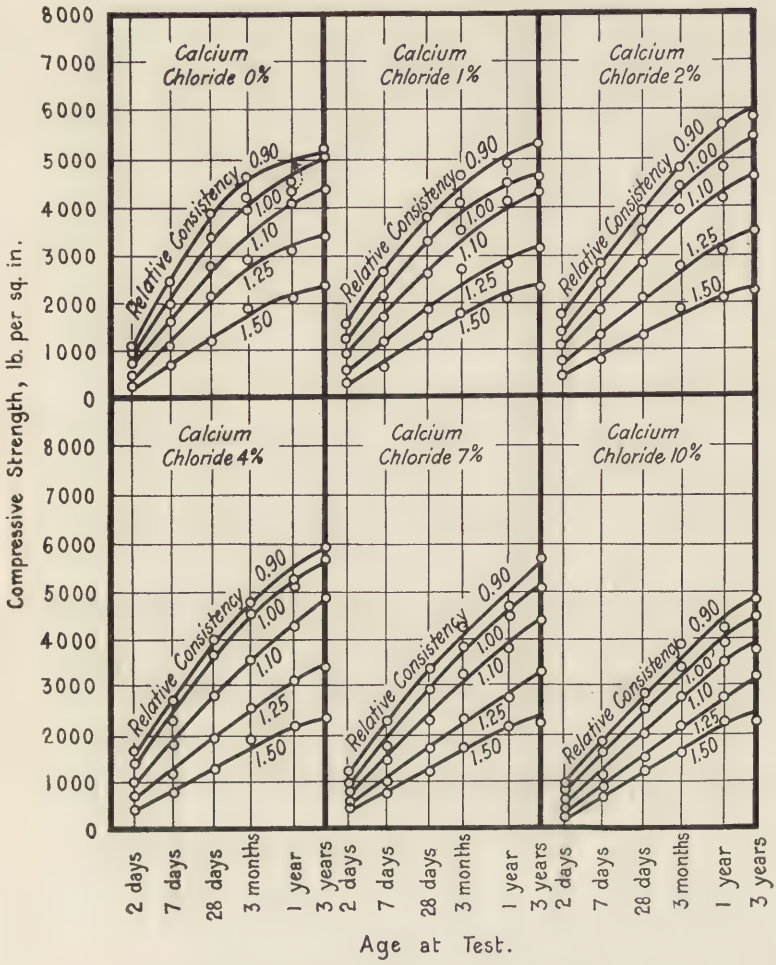


FIG. 13.—Effect of Age on the Strength of Concrete.

Compression tests of 6 by 12-in concrete cylinders cured in moist room.
Age plotted to logarithmic scale.
Mix 1:5.2 by volume.
Calcium chloride *B* was used.
Each value is the average of 5 tests made on different days.
Data from Table IV; compare Figs. 12, 14, and 15.

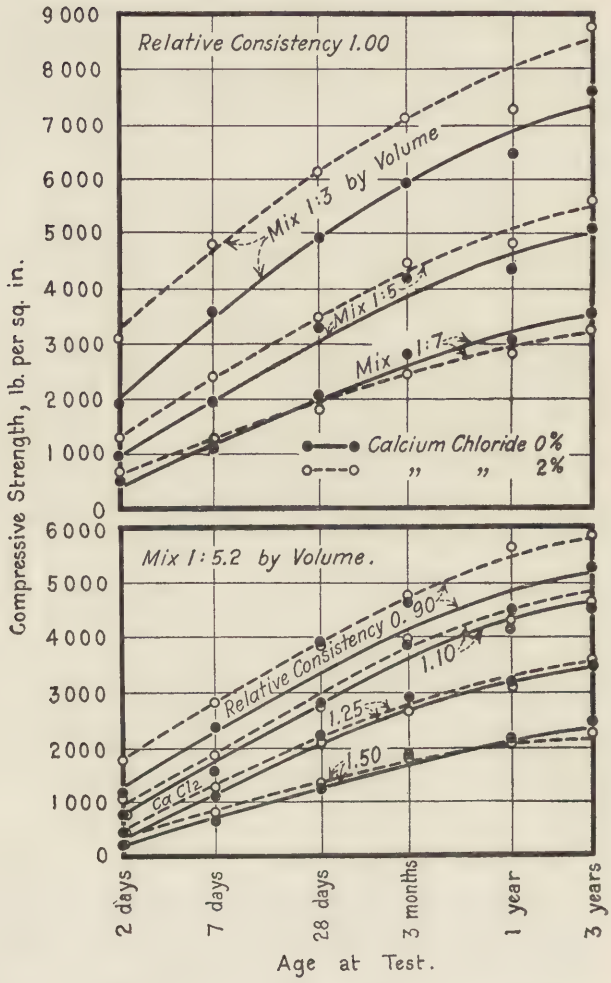


FIG. 14.—**Effect** of Calcium Chloride on the Strength of Concrete as Influenced by Age at Test.

Compression tests of 6 by 12-in. concrete cylinders cured in moist room.
Age plotted to logarithmic scale.
Calcium chloride *B* was used.
Each value is the average of 5 tests made on different days.
Data from Tables III and IV; compare Figs. 12, 13 and 15.

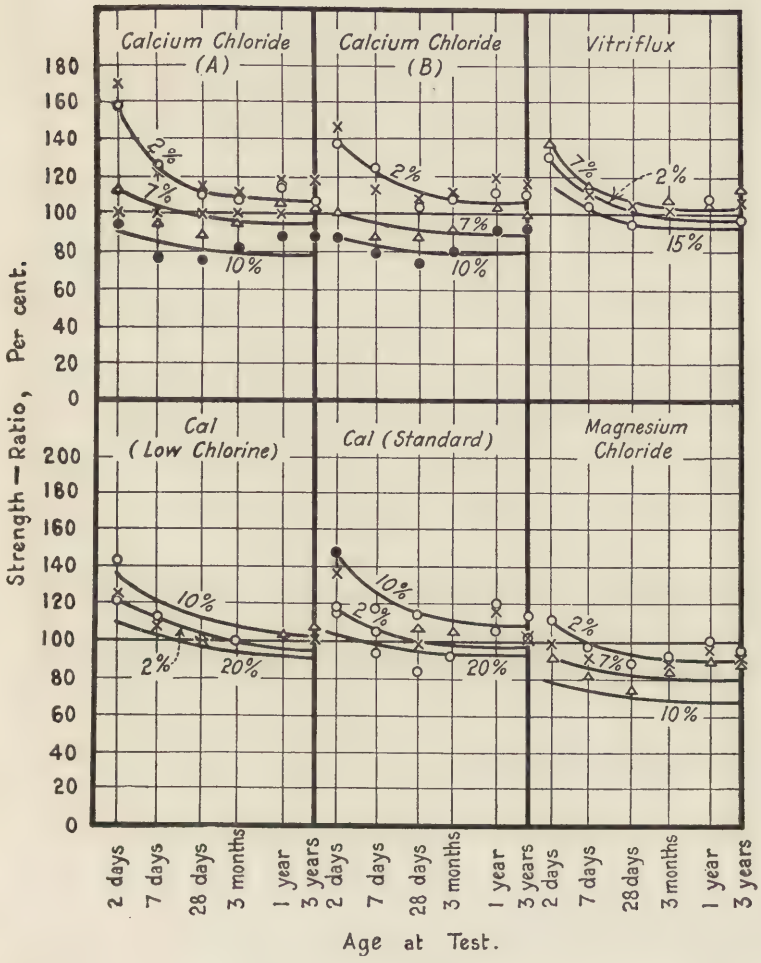


FIG. 15.—Effect of Different Admixtures on the Strength of Concrete as Influenced by Age at Test.

Compression tests of 6 by 12-in. concrete cylinders cured in moist room.
Age plotted to logarithmic scale.
Mix 1:5.2; relative consistency 1.00.
Each value is the average of 4 to 10 tests made on different days.
Data from Table I; compare Figs. 12, 13, 14 and 16.

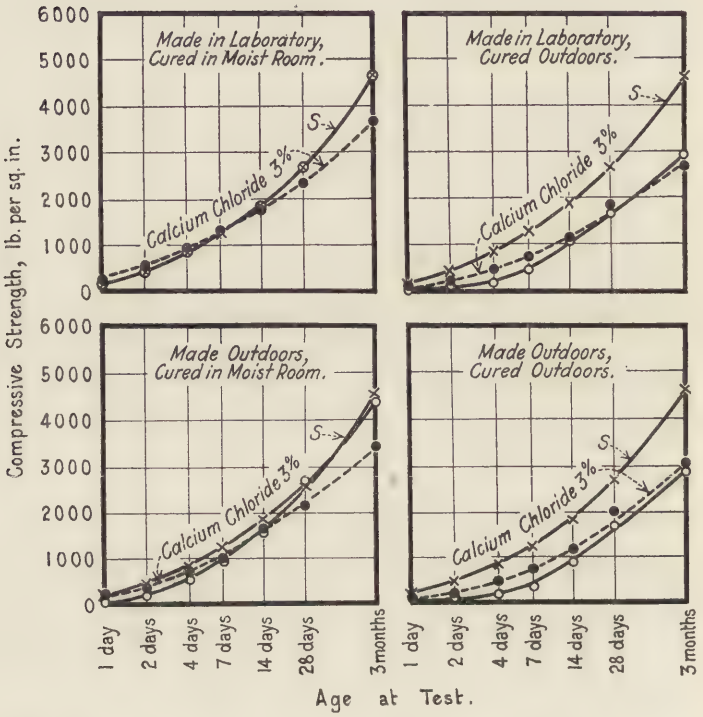


FIG. 16.—Tests of Concrete Made and Cured at Low Temperatures.

Compression tests of 6 by 12-in. concrete cylinders.
Age potted to logarithmic scale.
Mix 1:5 by volume; relative consistency 1.25.
Calcium chloride *A* was used.
Each value is the average of 6 tests made on different days
Data from Table IX.
Curve *S* repeated on each diagram for comparison.

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"Effect of Calcium Chloride on Portland Cement," by H. Burchartz, *Mitteilungen* a. d. kgl. Versuchsanstalten zu Berlin, Vol. 28, p. 338, 1910. *Journal*, Soc. Chemical Ind., Vol. 29, p. 108, 1910.

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Value of material investigated and results given.

"Effect of Cal on Corrosion," by J. C. Witt, *Concrete* (CMS), p. 154, February, 1921.

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"Influence of Calcium Chloride on Tensile and Compressive Strength of Portland Cement," by C. R. Platzmann, *Zement*, Vol. 10, p. 499, October 6, 1921. Abstract, *Chimie et Industrie*, Vol. 7, p. 943, May, 1922. *Chemical Abstracts*, Vol. 16, p. 2586, 1922.

"Industrial Chemistry Problem Relative to Treatment of Cement (Influence of Addition of Calcium Chloride on Strength of Portland Cement)," by C. R. Platzmann, *Zement*, Vol. 11, pp. 137, 151, 1922. *Chimie et Industrie*, Vol. 8, p. 614, 1922. *Chemical Abstracts*, Vol. 16, p. 4318, 1922.

Calcium chloride (2.4 to 5 per cent) added to mixing water to hasten setting and prevent shrinkage. Tensile and compressive strengths tabulated with different percentages of $CaCl_2$. Increased constancy of volume and generation of heat during setting. Concrete containing calcium chloride less readily attacked by gases which in presence of water form H_2SO_3 and H_2SO_4.

"Calcium Chloride and Cement," by F. Killig, *Zement*, Nos. 45 to 48, 1922. *Chem. Zentr.*, Vol. 94, p. 462, 1923.

Use of calcium chloride up to 7 per cent added to cement in mixing water superior to grinding with cement.

"Calcium Chloride in Concrete Highway Construction," by Piepmeier and Clemmer, *Engineering News-Record*, Vol. 88, p. 409, March 9, 1922.

Laboratory and field tests indicate accelerated setting and more economical curing method than usual practice.

"Calcium Chloride in Concrete," *Concrete*, Vol. 20, p. 176, April, 1922.

Reduces time of set and may prevent freezing before setting. Not recommended in reinforced concrete exposed to extreme moisture.

"Use of Calcium Chloride as Protection Against Freezing of Concrete," by Cottringer and Kendall, *Concrete*, p. 150, April, 1923.

Tests made by Dow Chemical Co., Midland, Mich.

"Comparative Bonding Strength of Portland Cement Mortar," by J. R. Lapham, Pamphlet by Cal Chemical Co., Hagerstown, Md.

"How to Cure Concrete," Booklet published by Dow Chemical Co., 1923.

Use of "Dowflake" calcium chloride, economies, method of patching, quantity, application, etc.

"Strength of Cal Mortar in Laying Brick Work," *Concrete*, Vol. 22, p. 231, June, 1923.

Tensile, compressive, and bond tests of mortar, using Hytex brick with 5 per cent Cal added to mortar. Increase in strength found over mortar without Cal.

"Effect of Accelerators on Reinforcing Steel," *Engineering and Contracting*, Vol. 60, p. 202, July 25, 1923.

Steel in 1:2:4 concrete and 1:3 mortar specimens examined by the U. S. Bureau of Standards after outdoor storage for 5 or 6 years. Tests also made using metal

lath in slabs. Corrosion of metal due to calcium chloride was not serious nor of progressive nature when metal was completely embedded. Pockets near reinforcing should be avoided.

"Report of Cooperative Series of Tests on Accelerators," *Proceedings*, Am. Soc. Testing Mats., Vol. 23, Part I, p. 223 (1923). Abstract, *Engineering and Contracting*, Vol. 60, p. 358, August 22, 1923.

Tests made using different accelerators, by U. S. Bureau of Standards, Lehigh Portland Cement Co., City of Philadelphia, Lewis Institute, Hydro-Electric Power Commission, Pennsylvania State Highway Commission, Delaware State Highway Commission, and New Jersey State Highway Commission.

"Effect of Curing Methods on Concrete Roads," by H. J. Kuelling, *Engineering News-Record*, Vol. 91, p. 466, September 20, 1923.

Tests of methods of curing road slabs to determine effects on wear and transverse strength. Coverings of sodium silicate, calcium chloride, hay, straw, and dirt used.

"Twelve-Hour Compressive Strength Tests," *Municipal Improvements* (Canada Cement Co., Montreal), p. 24, July, 1923.

Results of tests on 1:1 to 1:3 standard sand mortars, with and without calcium chloride up to 5 per cent by weight of cement, and different temperatures of mixing water.

"An Investigation in the Use of Calcium Chloride as a Curing Agent and Accelerator of Concrete," by H. F. Clemmer and Fred Burggraf, *Proceedings*, Am. Soc. Testing Mats., Vol. 23, Part II, p. 296 (1923). *Engineering News-Record*, Vol. 91, p. 143, 1923.

Over 500 slabs, 30 by 12 by 8 in., and 6 by 12-in. cylinders made of 1:2:3½ concrete cured in various ways. Slabs cured by spreading 1 to 3 lb. of dry calcium chloride per square yard had higher modulus of rupture than ordinary curing which enables use of concrete sooner than ordinarily; lumps detrimental. Illinois Highway Specifications require 2½ lb. of calcium chloride flakes spread uniformly on each square yard 6 to 8 hours after concrete is laid. Solution of calcium chloride not sufficient; materials must not be applied during rain, but rain 2 or 3 hours after application will do no harm. Calcium chloride, not more than 2 per cent by weight of cement, may be dissolved in mixing water for use in cold weather, but is not to be used in reinforced concrete, nor near electric railroad crossing.

"Devices for Application of Calcium Chloride in Road Work," *Engineering and Contracting*, Vol. 61, p. 226, 1924.

Describes two devices for spreading calcium chloride.

FOREWORD

This paper was originally published in the Copyrighted Proceedings of the American Society for Testing Materials, Vol. 24, Part II, 1924. The discussion which appears in the Proceedings has been omitted.

In Tables 1 and 4, 1-year tests have been added since the publication of this report by the A.S.T.M. No changes in the general conclusions were necessary due to the addition of the 1-year tests.

Acknowledgment is made to the Society for permission to reprint the paper in bulletin form.

EFFECT OF END CONDITION OF CYLINDER ON COMPRESSIVE STRENGTH OF CONCRETE

By Harrison F. Gonnerman

Summary and Conclusions

Compression tests were made at 7 and 28 days, 3 months and 1 year on about 3000 6 by 12-in. concrete cylinders in a study of the influence of the following factors on the reliability of the test results:

(*a*) Position of spherical bearing block;
(*b*) Deflection of table of testing machine;
(*c*) Material used for capping;
(*d*) Condition of capping;
(*e*) Molding with uneven base and cover plates;
(*f*) Inclination of axis, and top surface.

The cylinders were made from 1:7, 1:5, 1:3½ and 1:2 concrete mixed to a relative consistency of 1.10; for a few conditions, tests were made on the 1:3½ mix using relative consistencies 0.90 to 2.00.

The data of the tests were compared and the relative value of the different methods of testing or capping was judged principally by the ratio of the strength obtained for a given method of test to that obtained for the standard method. The mean variation of the tests was used as a measure of the uniformity of the different methods.

The principal conclusions from the tests are:

1. The standard method of molding and capping concrete cylinders with machined base and cover plates gave uniformly high strength equal to or greater than that from any of the other methods.

2. Deflection of the table of the testing machine used was small and had practically no effect on the test results.

3. For reliable results the use of the adjustable block with spherical bearing surfaces was found to be essential. A spherical bearing block with hardened steel balls between the spherical surfaces gave essentially the same results as the plain spherical block.

4. No difference in results was found when spherical bearing blocks were used in the following positions:

(*a*) On top of cylinder;
(*b*) Inverted on top of cylinder;
(*c*) Beneath the cylinder;
(*d*) Both on top and beneath the cylinder.

5. Small errors ($\frac{1}{4}$ in. or less) in centering the bearing block on the cylinder had little or no effect on the test results. An error of $\frac{1}{2}$ in. in setting, gave strength-ratios of about 90 per cent for 1:5 and 1:3$\frac{1}{2}$ concrete.

6. Cylinders molded on a plane cast-iron base and with top trowelled smooth, showed the following results when tested as indicated:

(*a*) With thin caps of gypsum or mixtures of cement and gypsum, the results were essentially the same as those obtained for the standard method of capping.

(*b*) Without bedding, the strength-ratios obtained were about 95 per cent for 1:7 concrete, 94 per cent for 1:5 concrete and 80 per cent for 1:3$\frac{1}{2}$ concrete.

(*c*) With sheet materials between top of cylinder and the spherical block, the strength-ratios obtained were less than 100 per cent for all of the materials used.

(*d*) For the sheet materials, the best results were obtained with Beaver Board, which gave strength-ratios of about 100 per cent for 1:7 and 1:5 concrete and about 90 per cent for 1:3$\frac{1}{2}$ concrete.

(*e*) For white-pine board, mill board and leather, the strength-ratios ranged between those found for Beaver Board and those found for no bedding (see (*b*) above).

(*f*) For the other sheet materials, blotting paper, sheet lead and rubber, the strength-ratios were less than those found for no bedding.

(*g*) The lowest strength-ratios were found for the $\frac{1}{16}$-in. sheet rubber; they were about 80 per cent for 1:7, 70 per cent for 1:5 and 50 per cent for 1:3$\frac{1}{2}$ concrete.

7. Cylinders made and capped by the standard method, tested with a $\frac{1}{2}$-in. segment (circular segment of $\frac{1}{2}$-in. mid-ordinate) of the cap removed, gave strength-ratios slightly less than 100 per cent. When a 1-in. segment was removed the strength-ratios obtained were 100 per cent for 1:7 concrete, about 95 per cent for 1:5 concrete and 90 per cent for 1:3$\frac{1}{2}$ concrete. The removal of a 2-in. segment gave strength-ratios of 90, 80, and 65 for the three concretes.

When the segments removed were replaced with 1:1 gypsum and cement mortar 3 hours before test, the strength-ratios were about 100 per cent except for the 2-in. segment, which showed strength-ratios of from 95 to 90 per cent.

8. Cylinders with plane parallel ends but with axes inclined, gave the same strength as standard cylinders for an inclination of $\frac{1}{4}$ in. in 12 in. and strength-ratios of about 92 per cent for an inclination of $\frac{1}{2}$ in. in 12 in.

9. Cylinders with the top surface inclined showed strength-ratios of about 100 per cent for an inclination of $\frac{1}{4}$ in. in 6 in. and of about 95 per cent for an inclination of $\frac{1}{2}$ in. in 6 in.

10. Cylinders molded with machined cast-iron plates so as to give convex ends and tested without bedding, gave pronounced reductions in strength even for a small amount of convexity. The reduction in strength increased with increase in convexity and with increase in the richness of the mix.

For a convexity of 0.01 in. the 1:3½ and 1:2 mixes showed strength-ratios of about 65 per cent and for a convexity of 0.05 in., about 40 per cent. For the 1:7 and 1:5 mixes the corresponding strength-ratios were about 80 and 55 per cent.

When tested with Beaver Board sheets at both top and bottom, the reductions in strength were about half as great as when tested without bedding.

The use of gypsum bedding for one group of cylinders with bases convex 0.05 in. gave strength-ratios of about 90 per cent.

11. The effect of concave ends was small compared to that of convex ends.

12. Sheared steel plates 8 in. square by $\frac{1}{4}$ in. thick, from warehouse stock, showed deviations from a true plane of as much as 0.012 in. Cylinders molded with these plates as bases and covers so as to give convex ends, gave results comparable with those from cylinders having the same convexity similarly made with machined cast-iron plates (see 10 above).

13. Tests with concrete of different consistencies using cylinders with ends convex about 0.01 in. showed similar results for all consistencies. The typical relation of strength to water-cement ratio was found.

14. The different conditions of test did not show a marked difference in the uniformity of the individual results. The average mean variation of the 28-day tests ranged from 4.1 per cent for one group of the standards to a maximum of 10.9 per cent for the cylinders tested without an adjustable bearing block.

15. Finally, the most important conclusion from these tests is that great care must be exercised when preparing cylinders for test in order to secure ends which are true planes. When the standard method of capping with plane cover plates cannot be followed, the cylinder should be trowelled smooth and bedded with a thin layer of gypsum or a mixture of gypsum and cement 3 to 6 hours before test. The cylinders should always be molded on a plane surface.

EFFECT OF END CONDITION OF CYLINDER ON COMPRESSIVE STRENGTH OF CONCRETE

By Harrison F. Gonnerman

Introduction

In making compression tests of concrete it has long been recognized by testing engineers that proper capping or bedding of the ends of the test cylinders is of prime importance. Experience and tests have shown that without a certain degree of care and uniformity in preparing the ends, the results will show considerable variation among themselves and may not be truly indicative of the strength of the concrete. The general adoption by testing laboratories of the methods of making and testing concrete specimens recommended in the "Standard Methods of Making and Storing Specimens of Concrete in the Field" (Serial Designation: C 31 – 21)[1] and in the "Tentative Methods of Making Compression Tests of Concrete" (Serial Designation: C 39 – 21 T),[2] of the American Society for Testing Materials has tended toward greater uniformity in test results. However, facilities are not always available nor conditions favorable for carrying out the recommendations in complete detail, and as there is an increasing demand for the testing of field concrete, it has seemed of sufficient importance to warrant the further investigation of methods of preparing cylinders for test which will insure reliable results without undue delay or expense.

The tests described in this paper were carried out primarily to determine the influence of uneven end surfaces and of different methods of capping on the reliability of compression tests of 6 by 12-in. concrete cylinders. Studies were also made of the effect of such factors as the deflection of the bed of the testing machine and the use of spherical bearing blocks in different positions.

About 3000 cylinders of four different mixes of concrete were used in the investigation.

These tests form a part of the experimental studies of concrete and concrete materials being carried out at the Structural Materials Research Laboratory through the cooperation of Lewis Institute and the Portland Cement Association.

[1] 1924 Book of A.S.T.M. Standards, p. 762.
[2] 1923 Book of A.S.T.M. Tentative Standards, p. 300.

OUTLINE OF TESTS

Two series of tests were carried out for the purpose of studying the influence of the following factors on the reliability of test results:

(*a*) Position of spherical bearing blocks;
(*b*) Deflection of table of testing machine;
(*c*) Material used for capping;
(*d*) Condition of capping;
(*e*) Molding with uneven base and cover plates;
(*f*) Inclination of axis, and top surface.

The first (Series 179) comprised compression tests of about 2100 6 by 12-in. concrete cylinders in which a range of mixes was selected that would include concrete of the quality ordinarily employed in construction work. The concrete mixes used (1:7, 1:5, 1:3½) were all of relative consistency 1.10 and the cylinders were generally tested at 28 days. For several of the methods studied, cylinders were made also for test at 7 days, 3 months, and 1 year.

The second series of tests (Series 179*A*) consisted of compression tests on about 900 cylinders. Most of the tests in this series were made to study the effect of unevenness in the top and bottom surfaces of the test cylinder on the load carried and on the uniformity of the results. The use of a Beaver Board sheet in overcoming the ill effects of poorly prepared ends was studied. Further studies of the position of the bearing block, deflection of the table of the testing machine and inclination of the axis and top surface of the cylinders were made. Four concrete mixes, 1:7, 1:5, 1:3½ and 1:2, of relative consistency 1.10 were tested; for a few conditions tests were made on the 1:3½ mix using relative consistencies 0.90, 1.00, 1.25, 1.50 and 2.00. The cylinders were tested at 28 days.

CONCRETE MATERIALS AND PROPORTIONS

All concrete cylinders were made with portland cement consisting of a mixture of four brands purchased in Chicago. The same cement was used in both series; the neat cement used for capping was from the same lot. The results of chemical analysis, miscellaneous and physical tests of the cement are given in Table 8.

The aggregate for concrete was sand and pebbles from Elgin, Ill., graded 0 to 1½ in. In order to reduce the variations in grading to a minimum the aggregate was screened into four sizes (0 to No. 4, No. 4 to ⅜ in., ⅜ to ¾ in., and ¾ to 1½ in.) and recombined to a predetermined sieve analysis. The fineness modulus of the mixed aggregate was 5.65.

The proportions of cement and aggregate reported in the tables are expressed as one volume of cement to a given number of volumes of dry rodded aggregate mixed as used. The quantities of each batch were determined by weight.

The concrete for most of the tests was mixed to a relative consistency of 1.10 which gave a flow of about 220 per cent when measured by means of the flow table using fifteen $\frac{1}{2}$-in. drops in 10 seconds.[1]

TEST PIECES

The concrete specimens used in comparing the various methods of testing were 6 by 12-in. cylinders. Ten cylinders made on different days were used for each condition of test. Each cylinder was made from a batch of about $\frac{1}{5}$ cu. ft. proportioned separately and mixed by hand with a blunted bricklayer's trowel in a shallow metal pan.

The concrete cylinder forms were of cold-drawn steel tubing slotted along one element. In making the cylinders, the forms were generally placed on cast-iron plates machined to a plane surface. In the studies of the effect of uneven and dished ends, the cylinders were molded on machined cast-iron or sheared steel plates or on pine boards as indicated in the tables. In studies of the effect of inclining the axis and the top surface of cylinder, the ends of the steel molds were cut to give the desired inclination.

The concrete was placed in the forms in 3 layers, each layer being rodded 30 times with a $\frac{5}{8}$-in. bullet-pointed steel rod. After molding, the specimens were capped as described below.

All concrete specimens were cured in a room the air of which was saturated with moisture and in which a uniform temperature of about 70° F. was maintained. Three days prior to test, the cylinders were removed from the moist room and cured in the air of the laboratory. Most of the tests were made at the age of 28 days. For a few conditions specimens were also made for test at 7 days, 3 months and 1 year.

Methods of Capping and Preparing Cylinders for Test.—The standard method of capping the cylinders was as follows: 2 to 6 hours after molding, a fairly stiff neat cement paste, which had been mixed previously and allowed to stand from 2 to 6 hours, was placed on the top of the cylinder. This paste was covered with a machined cast-

[1] The dimensions of the truncated cone-shaped metal form used for the flow test were: top diameter 6¾ in., bottom diameter 10 in., height, 5 in.

iron plate about $\frac{1}{2}$ in. thick and 8 in. in diameter which was pressed down with a sliding and turning motion until it rested on the top of the cylinder form (see Fig. 1). By allowing the neat cement paste to stand for several hours before use, the tendency of the cap to shrink was largely overcome. Adhesion of the concrete to the capping plate and to the base plate was prevented by placing a sheet of paraffined tissue paper between the plate and the test specimen. If the capping paste became too stiff before use a small quantity of water was added and the paste remixed. It was generally not necessary to add water unless the paste stood for about 6 hours.

When specimens were capped with gypsum and with mixtures of portland cement and gypsum a small amount of the capping material was placed on a planed cast-iron table top and the trowelled top of the cylinder pressed down upon it to form a thin smooth cap. The table top was oiled to prevent the capping material from adhering when hardened. Care was taken to keep the cylinder in a vertical position during the capping operation in order to obtain parallel ends.

In a few tests the surfaces of the cylinder were capped in the testing machine with gypsum paste which was allowed to harden under load. The cylinder was placed in a bed of gypsum paste on the weighing table of the machine and the top of the cylinder covered with paste. The head of the testing machine with a spherical bearing block was then run down upon the cylinder until a load of about 750 lb. (25 lb. per sq. in.) was applied. The load was kept on the cylinder until the paste had hardened for 6 hours, when the test was completed. In the tests where a plane cast-iron base plate was used in molding the specimens, only the top surface of the cylinder was capped.

In some of the tests the cylinders were capped in a manner similar to that described for the standard method except that uneven and warped cover plates were used. In other tests the tops of the cylinders were trowelled to a smooth surface when molded and left to be capped at the time of test or to be tested using sheet materials as a substitute for capping.

For one set of specimens (Ref. 27, Table 2) the tops were ground to a smooth plane surface in a surface grinder and were tested without additional capping.

The gypsum used for capping was No. 1 molding plaster manufactured by the U. S. Gypsum Co. Data of compression tests of the portland cement and gypsum mortar used for capping are given in Table 7.

SHEET MATERIALS AS SUBSTITUTES FOR CAPPING

Eight different kinds of sheet materials were used as substitutes for neat cement and gypsum capping to determine to what extent they would minimize the ill effects of poorly prepared ends. The sheet materials were cut into pieces about 7 in. square and were placed between the surface of the cylinder and the spherical block or the bottom bearing plate.

The materials used were:

Beaver Board.—A commercial wall board $\frac{3}{16}$ in. thick; manufactured by The Beaver Board Companies, Thorold, Ontario, Canada.

Blotting Paper.—A cotton blotting paper $\frac{3}{32}$ in. thick.

Cork Carpet.—No. 2 Armstrong Carpet $\frac{5}{16}$ in. thick; manufactured by the Armstrong Cork Carpet Co., Lancaster, Pa.

Lead.—Sheet lead $\frac{1}{16}$, $\frac{1}{8}$ and $\frac{1}{4}$ in. thick.

Leather.—Oak tan leather, 2-ply, $\frac{5}{32}$ in. thick.

Mill Board.—16-ply cardboard, $\frac{1}{16}$ in. thick.

Rubber.—Rubber sheeting, $\frac{1}{16}$, $\frac{1}{8}$, and $\frac{1}{4}$ in. thick.

White Pine Board.—$\frac{1}{8}$ in. thick, planed on both sides.

METHODS OF TESTING

All concrete specimens were tested in a 200,000-lb. universal testing machine except those for Ref. 10 in Table 1 which were tested in a 300,000-lb. machine. Unless otherwise stated, a spherical bearing block was placed on top of the cylinder as indicated in Fig. 2. The bearing block was designed and made in the laboratory shops.[1]

In tests of Ref. 4 and 104, a bearing block, the spherical surfaces of which were separated by hardened steel balls (see Fig. 2) was used. In order to determine the influence of the position of the spherical bearing block on the test results, cylinders were tested as follows:

Bearing block on top of cylinder;
Bearing block beneath cylinder;
Bearing blocks both on top and beneath cylinder;
Bearing block inverted on top of cylinder;
Bearing block off center $\frac{1}{16}$, $\frac{1}{8}$, $\frac{1}{4}$ and $\frac{1}{2}$ in.

One set of cylinders in each series was tested without a spherical bearing block.

Except as indicated in the tables, the cylinders were tested on a machined steel distributing plate 4 by 13 by 24 in. in size placed on the weighing table of the testing machine. The purpose of this plate was to eliminate possible ill effects resulting from the deflection of the weighing table of the testing machine, particularly at loads near the capacity of the machine.

[1] For a description of the method used in machining the spherical bearing surfaces of this block, see *American Machinist*, p. 26, January 3, 1924.

DATA AND DISCUSSION

Standard of Comparison.—This investigation was undertaken to compare the reliability of the results obtained for several conditions of test. In order that variation in the concrete itself might not confuse the variations resulting from the different conditions used, it was important that the concrete be of uniform strength. In the preparation of the cylinders, the usual care was taken to obtain uniform materials and to make the cylinders in such a way that accidental errors of manipulation would be distributed throughout the series so that no one set of specimens would be unduly affected.

For convenience in reporting and studying the data, the basis of comparison for each series of tests was a group of specimens made and tested in accordance with the methods described in the "Tentative Methods of Making Compression Tests of Concrete" (Serial Designation: C 39 – 21 T) of the American Society for Testing Materials, which are the standard practices of this laboratory.

The cylinders for standard condition of test were:

1. Molded on plane, machined cast-iron base plates;
2. Capped when made;
3. Capped with neat cement which had been mixed and allowed to stand from 2 to 6 hours before use; a machined cast-iron cover plate was used to produce a cap having a plane surface;
4. Tested with spherical bearing block placed on top of specimen.

In the first series it was originally planned to use the tests of the specimens for Ref. 1, Table 1, as the standard of reference and to compare the results of other methods of test with this standard by means of strength-ratios, that is, the ratio (expressed as a percentage) of the average strength for a given method of test to the average strength for the standard method. However, a study of the data in Table 1 showed that several of the methods of test gave strength-ratios from 95 to 100 per cent and that the mean variations for these groups did not differ greatly from those shown for the standard group. Furthermore, the variation of the average of these groups from the standard was no greater than the variations within the standard group itself. From these considerations, it seemed desirable to include in the group of specimens forming the standard of reference those values in Table 1 which represented essentially the same conditions, and thus base the comparisons on a more representative number of specimens. Therefore in the study of the data in Tables 1 to 4, comparisons are based on the average of all tests for Ref. 1 to 4.

The method of test chosen as the standard is one which has been found to give reliable results. It permits of the failure of the specimen without restraint other than that induced by the friction between the end surfaces of the cylinder and the adjacent bearing plates which in this case is not important because of the length of specimen used. Such influences as splitting action due to the use of a yielding capping material, eccentricity of load, etc., are eliminated. This being true, it might be expected that an unfavorable method of test, besides showing a greater variation in the individual results from the average would also show a strength-ratio of less than 100 per cent. In the study of the data, therefore, the comparative value of the different methods of test is judged by the reduction in strength, as indicated by the strength-ratio, as well as by the uniformity of results as indicated by the mean variation. The mean variation is the average variation of the strengths of individual specimens from the average strength of the group. In the tables, the mean variation is expressed as a percentage of the average strength.

In the second series of tests (179*A*) comparisons are based on the group of specimens Ref. 101 (Table 5) originally selected for this purpose. The tests for Ref. 103 and 104 show the same close agreement noted in Table 1 for similar conditions. The values for these two conditions might well have been included in the standard of comparison for this series, but their inclusion would not have affected the results since their strength-ratios and mean variations are essentially the same as Ref. 101.

Influence of Position of Bearing Blocks and Deflection of Bed Plates on Test Results.—In the foregoing discussion it was pointed out that the use of a spherical bearing block beneath the cylinder, both above and beneath the cylinder, and a bearing block the spherical surfaces of which were separated by hardened steel balls gave essentially the same results as when a spherical bearing block was placed on top of the cylinder, and that the standard of comparison was made to include the tests for these conditions. The equally close agreement in the similar tests in Table 5 was also pointed out.

The tests in which the spherical bearing block was not used (Ref. 5, Table 1) show a reduction in strength of from 8 to 19 per cent and a higher mean variation, especially for the stronger concrete. Data from similar tests for a 1:2 mix in Table 5 (Ref. 105) show a reduction in strength of 18 per cent and a mean variation about three times that for the standard condition. It follows from these results that the use of this method of test is not to be recommended.

The three groups of tests (Ref. 6, 7, and 8, Table 1) in which the setting of the spherical bearing block was varied, show that for the 1:5 concrete tested, placing the bearing block off center as much as $\frac{1}{4}$ in. produced no noticeable effect on the strengths or on the reliability of the results. The strength-ratios for these three conditions in the first series were 100 per cent; the mean variations were about the same as the average for Ref. 1 to 4.

The tests in Series 179*A* (Ref. 106 and 107, Table 5) for bearing block off center $\frac{1}{8}$ in. and $\frac{1}{4}$ in. showed strength-ratios of only 93 and 92 per cent for the 1:5 mix and 99 and 97 per cent for the 1:3$\frac{1}{2}$ mix. Considering the limit of accuracy to be expected, this is a fair corroboration of the earlier tests. For the bearing block $\frac{1}{2}$ in. off center (Ref. 108) the strength-ratios were 90 per cent for the 1:5 mix and 92 per cent for the 1:3$\frac{1}{2}$ mix. The values of mean variations for these tests were in general not materially different from those for the standard of comparison.

In the studies of the influence of deflection of bed plates, the deflection of the plates used to support the cylinder and of the table of the testing machine were measured for several of the tests. The measured deflections at loads of 30,000, 60,000 and 125,000 lb. which corresponded to the total loads at failure of cylinders from the three grades of concrete were as follows:

Plate and Span	Measured Deflection in Inches Corresponding to Load at Failure of Cylinder		
	1:7 Mix	1:5 Mix	1:3½ Mix
Table of testing machine in span of 32 in.	0.008	0.016	0.033
4 by 13-in. plate, 23½-in. span	0.005	0.010	0.021
2⅝ by 8 5/16-in. plate, 16⅝-in. span	0.007	0.014	0.030

When expressed as a deflection in a length equal to the width of the cylinder the values for the richer mixture reduce to approximately 0.003 in. for the table of the testing machine 0.005 in. for the 4-in. plate and 0.010 in. for the 2$\frac{5}{8}$-in. plate and to about one-half these values for the 1:5 mix and to one-quarter for the 1:7 mix.

While the results for the tests bearing on the question of deflection of bed plates (Ref. 9, 11 and 12) are not entirely consistent; when strength-ratios are plotted in terms of amount of deflection, an indication of reduced strength with increased bending in the plate is found. In Series 179*A*, the tests without the distributing plate were repeated (Ref. 102) using a richer mix than in the previous tests. The data show no reduction in strength for this mix (1:2). It may be concluded,

therefore, that the reliability of the tests of the cylinders placed directly on the table of the testing machine used is entirely satisfactory. However, the use of a distributing plate or block is recommended in tests of specimens of high strength or where a considerable deflection in the bed of the machine is known to exist.

The tests using the 300,000-lb. machine without the distributing plate beneath the cylinder (Ref. 10) show a very satisfactory mean variation, and an average strength-ratio slightly above normal.

Influence of Capping Materials and Methods of Capping.—Ref. 14 to 26, Table 2 show the results of using different materials for capping the top of the cylinder at the time of test. The bottoms of the cylinders for these tests were molded to a true plane and the tops trowelled off level with the form. The strength-ratios for these groups varied from 95 to 104 per cent and no systematic variation was apparent for the different conditions or mixes. These tests show that capping the top of the cylinder with any of the gypsum or mortar mixtures in the manner indicated, produced results substantially the same as the standard method in which the top of the cylinder was capped with neat cement at the time of making. That the tests are equal to the standard in reliability is also indicated by the uniformly low values of mean variation.

When the cylinders with the trowelled top were tested without capping (Ref. 13), the strength was reduced 4 to 6 per cent for the 1:7 and 1:5 mixes and about 20 per cent for the 1:3½ mix, although there was no appreciable increase in the mean variation of the individual results. This method of test is not recommended even for the weaker concretes.

When the top of the cylinder was ground to a smooth surface (Ref. 27), no reduction in strength was found and the average value of the mean variation for the three mixes was very low. This method of preparing cylinders for test, while quite costly for the occasional individual test, might well prove economical where a large number of tests are to be made on specimens with irregular ends, such as cores drilled from pavements.

Sheet Materials as Substitutes for Capping.—Table 2 (Ref. 28 to 39) gives data of tests in which a variety of sheet materials were used between the top of the cylinder and the bearing block as a substitute for mortar capping. The top of the cylinder was trowelled to a smooth surface at the time of making and the bottom molded to a true plane by the use of a machined plate under the form. The strength-ratios and the average values of the mean variations at 28 days, for the three different mixes used in these tests are as follows:

Material	Thickness, in.	Strength-ratio, per cent of Average for Ref. 1 to 4,			Average Mean Variation, per cent
		1:7 Mix	1:5 Mix	1:3½ Mix	
Beaver Board	3/16	98	101	91	5.4
White Pine	1/8	92	99	87	7.0
Mill Board	1/16	101	92	81	6.4
Leather	9/32	96	91	82	7.1
Blotting Paper	3/32	92	97	77	7.2
Sheet Lead	1/16	95	88	74	9.1
	1/8	91	90	74	6.7
	3/16	89	88	77	5.7
Cork Carpet	5/16	93	87	70	6.8
Rubber	1/16	81	71	47	8.0
	1/8	89	77	65	10.6
	1/4	93	80	63	7.9

It is significant that for all of the sheet materials used there was a decided falling off in strength-ratio with increase in the richness of the mix although the mean variations were generally no greater for the richer mixes. The fact that the rubber sheet gave the greatest difference in results between the lean and rich mixes, indicates that the cause of the lower strength was a splitting action induced by the tendency of the sheet material to flow laterally when under load.

These tests show that for the cylinders of 1:7 and 1:5 mix, with carefully trowelled tops and molded plane bases, a $\frac{3}{16}$-in. sheet of Beaver Board placed between the top of the cylinder and the spherical bearing block was a fairly good substitute for a cap of mortar or gypsum. For the 1:3½ mix, the results were not so satisfactory.

Cap Partly Removed.—In handling cylinders, it sometimes happens that part of the neat-cement capping is accidentally chipped off. The tests in Table 3 were made to determine how much of the capping might be removed without causing an appreciable reduction in strength. The data show that removing the cap for a distance of ¼ to ½ in. from the edge, that is, removing a circular segment of mid-ordinate ¼ to ½ in. produces no material reduction in strength nor change in mean variation. This method of test may be considered to produce an effect somewhat similar to that resulting from the use of a spherical bearing block off center and the results show the same general trend as those obtained with eccentric bearing block.

Where the cap was removed for a distance of 1 in. there was a reduction in strength of about 7 per cent for the 1:5 and 1:3½ mixes; when 2 in. was removed, the reduction in strength ranged from 11 per cent for the 1:7 mix to 34 per cent for the 1:3½ mix.

When the segment of the cap was replaced with mortar, somewhat

better results were obtained for both the 1 and 2-in. segments, although for the latter condition there still remained a deficiency in strength of from 5 to 9 per cent.

Influence of Concave and Convex Ends.—Table 4 gives results of tests of cylinders having concave and convex ends. The ends were formed by molding and capping in the usual way with plates machined to convex and concave surfaces having maximum deviations from a true plane of about 0.003, 0.1 and 0.2 in. The cylinders were tested as the other pre-capped specimens, that is, with no bedding of either mortar or sheet material. In Series 179*A* further tests were made to show the effect of using similar plates machined to give cylinders with bottoms convex 0.01, 0.02 and 0.05 in.

The tops were trowelled smooth. Some of the cylinders were tested as made, without bedding; others were tested with sheets of Beaver Board at both top and bottom; one set was tested using gypsum-mortar bedding both top and bottom. Other cylinders were made in which the standard method of molding and capping was followed except that $\frac{1}{4}$-in. sheared steel plates were used for the base and cover plates. Field specimens are sometimes made using such plates, and as earlier tests showed that small irregularities affected the results very materially, the tests using sheared plates were included. Sheared plates were selected some of which were approximately true planes, and others which were dished or warped about 0.01 in. Cylinders were tested both without bedding and using Beaver Board sheets both top and bottom. Table 5 gives the results of the tests for Series 179*A*.

Fig. 3 shows data from both series plotted with strength-ratios as ordinates and amount of convexity or concavity as abscissas. Curves 1 and 2, which give results of tests on 1:5 concrete from Table 4, were transferred from a drawing of smaller scale as only one value fell within the range of abscissas covered by the figure. Except for the values corresponding to 0.003 in. convexity, which are about normal, these curves show that convex ends reduce the cylinder strength about four times as much as ends which are concave a similar amount.

The results of tests on cylinders with convex ends for different mixes and methods of test are shown in Table 5 (Ref. 117, 118, 119, 123, 124 and 125). These data can be more easily compared by the curves of Fig. 3. Curves 3, 4, 5, and 6 show the results for cylinders of 1:7, 1:5, 1:3$\frac{1}{2}$ and 1:2 concrete having molded convex bases and trowelled tops, tested without bedding of either mortar or sheet material. Curves 7, 8, 9 and 10 show the results for similar specimens tested with sheets of Beaver Board both top and bottom.

It will be noted that the cylinder strength is reduced in all cases with an increase in the amount of convexity and with the richness of the mix; also that the specimens tested using the Beaver Board sheets show a loss of strength about half as much as those tested without bedding.

The cylinders for Ref. 114 were of 1:3½ mix and had bases convex 0.05 in. and trowelled tops. They were tested with gypsum bedding top and bottom. When compared with similar specimens tested without bedding and with Beaver Board sheets (Ref. 119 and 125) the strength-ratios are as follows:

Kind of Bedding	Strength-Ratio, per cent
None	38
Beaver Board sheets top and bottom	75
Gypsum top and bottom	90

These strength-ratios show that while the gypsum bedding helped materially it did not entirely overcome the effect of the convex end. It should be noted that these comparisons are for rather rich concrete; for ordinary mixes the effect of the bedding in overcoming convexity would probably have been greater.

The significant feature of these tests of cylinders with convex ends is the marked effect of very small irregularities. It was because of the importance of this feature of the tests that the tests with the sheared steel plates (Ref. 115, 116, 121 and 122) were undertaken, as such plates are sometimes used. The sheared plates were from warehouse stock and were 8 in. square. They were carefully measured and those which showed a deviation of less than 0.004 in. from a true plane were classed as plane plates; those which were about 0.01 in. out of true were classed as warped plates. In molding the cylinders, the warped plates were used to give convex ends both top and bottom.

The data in Table 5 show that for the cylinders tested without bedding, those made using the sheared plates which were approximately plane showed a reduction in strength averaging 7 per cent; for the warped plates the reduction in strength ranged from 20 per cent for the 1:7 mix to 32 per cent for the 1:2 mix. When tested with Beaver Board sheets both top and bottom the reductions in strength for the two conditions were about one-half to one-third as great as when tested without the sheets. These results are not plotted in Fig. 3 but they agree fairly well with the strength-ratios shown by the curves when the amount of convexity is taken into account.

Table 6 (Ref. 127 and 128) gives data of further tests of cylinders molded with warped sheared steel plates top and bottom in such a way as to give convex ends. Parallel tests on cylinders of 1:3½ mix for six different consistencies were carried out. Some of the cylinders were tested without bedding and some with Beaver Board sheets top and bottom. The data from these tests are shown in Fig. 4 where compressive strengths are plotted against water-cement ratios. For purpose of comparison a curve based on tests of cylinders molded and tested in the standard way is included. The curves show a reduction in strength of from 2 to 9 per cent for the cylinders tested with Beaver Board and a reduction of from 17 to 30 per cent for those tested without bedding. The curves show quite clearly that the reduction in strength due to the convex ends is greater for the stronger concretes.

In plotting Fig. 4, the data from cylinders of other mixes, made and tested under similar conditions were included in order to obtain a wider range for the water-ratio-strength curves. These curves are similar in form to those given in other publications of this Laboratory, and show the important relation of the water-cement ratio to the compressive strength of the concrete.

It is apparent from these data that in tests of concrete care must be taken to secure cylinder ends that are true planes. This is the most important feature of this investigation. The loss of strength due to a small convexity of the cylinder end is very much greater than that due to inclinations of the axis or top surface of the cylinder as will be shown later.

Use of Pine Board Bases for Molding Cylinders.—Field specimens are frequently molded by placing the forms directly on a smooth board. Tests were made to approximate this condition. The molds were placed on a 1-in. pine board during the molding operation and the tops of the cylinders were trowelled smooth.

The cylinders (Ref. 120 and 126, Table 5) showed strength-ratios from 82 per cent for the 1:7 mix to 67 per cent for the 1:2 mix when tested without capping of any kind. When tested with sheets of Beaver Board both top and bottom the corresponding strength-ratios ranged from 98 to 79 per cent. The deviation of the cylinder bases from a true plane varied from a few thousandths to about one-tenth of an inch. As this represents what might be expected in cylinders similarly made in the field, the low strengths obtained are significant. The results are comparable to those obtained for cylinders with convex ends (see Fig. 3).

Influence of Inclined Axis and Inclined Ends.—Tables 4 and 5 (Ref. 54, 55, 109 and 110) give results of tests in which the ends

of the cylinders were parallel but the axis of the cylinder was inclined $\frac{1}{4}$ and $\frac{1}{2}$ in. from the vertical in a length of 12 in. The tests show that for parallel ends an inclination of the cylinder axis of $\frac{1}{4}$ in. caused no appreciable reduction in strength; an inclination of $\frac{1}{2}$ in. caused a reduction of from 5 to 8 per cent.

Data on tests of cylinders having their axes at right angles to the base but the top surface inclined $\frac{1}{4}$ and $\frac{1}{2}$ in. in a distance of 6 in. are given in Tables 4 and 5 (Ref. 56, 57, 111 and 112). These results show no reduction in strength where the top was inclined $\frac{1}{4}$ in. from the horizontal and about 5 per cent reduction for an inclination of $\frac{1}{2}$ in. These tests show how relatively unimportant are minor inclinations of the ends or axis in comparison with small convexities in the end surfaces.

Tests of Cylinders with Ends Greased or Wetted.—Wetting and greasing the cylinder top before testing (Ref. 58 and 59, Table 4), while showing very slight reductions in strength cannot be regarded as particularly significant, as the 2 per cent reduction found might easily be accounted for by the accidental variations occurring in any two sets of cylinders.

Uniformity of Results.—One of the interesting features of this investigation was the rather surprising uniformity exhibited by the cylinders tested by any of the methods tried. It was expected that the study of the mean variation would give considerable information on the relative value of the different methods of test. This expectation, however, was not fully realized. Except for a few of the methods used, the mean variation of the individual strengths from the average strength did not differ greatly from that shown by the group of cylinders used for the standards.

The greatest variation in individual results was found in the tests without adjustable bearing block (Ref. 5 and 105) for which the average mean variation for the 28-day tests of the four grades of concrete was 10.9 per cent; the highest value was 13.2 per cent for the 1:3½ mix. For this method of test, the mean variation for the 1:5 mix at 1 year was 16.2 per cent. For the tests with $\frac{1}{8}$-in. sheet rubber, high mean variations were also found. The values ranged from 7.9 to 12.4 per cent and averaged 10.6 percent. The lowest mean variations were found for the standard tests in Series 179*A* and for the cylinders with tops ground to a smooth surface; the values were 4.1 and 4.5 per cent, respectively. It appears that the reliability of a given method of test should not be judged solely by the mean variation of the individual test results from the average. The mean variation may be low but it does not necessarily follow that the strength obtained represents the true strength of the material tested.

TABLE 1.—INFLUENCE OF POSITION OF BEARING BLOCK AND DEFLECTION OF BED PLATE ON COMPRESSIVE STRENGTH OF CONCRETE—SERIES 179

Compression tests of 6 by 12-in. concrete cylinders.

Mix by volume.

Relative consistency 1.10 (Flow about 220).

Aggregate: sand and pebbles from Elgin, Ill., graded 0 to 1½ in. (Fineness modulus, 5.65.)

Cement: a mixture of four brands purchased in Chicago.

Cylinders molded on 8-in. cast-iron base plates machined to a plane surface.

Cylinders capped 4 to 6 hours after making with neat cement (mixed 4 to 6 hours before use).

Cylinders cured in moist room until 3 days prior to test; remainder in air of laboratory.

Cylinders tested using a 6-in. spherical bearing block carefully centered on top and a 4 by 13 by 24-in. steel distributing plate below unless otherwise noted.

Strength-ratio is the ratio, expressed as a percentage, of the strength obtained for a given method of test to the average strength for Ref. 1 to 4.

All tests made using a 200,000-lb. Universal testing machine except Ref. 10.

Each value is the average of 10 tests made on different days unless otherwise noted.

Reference	End Condition of Test Cylinder	1:7 Mix, 28 days			1:5 Mix													1:3½ Mix, 28 days		
					7 days			28 days			3 months			1 year							
		Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Mean Variation, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Mean Variation, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Mean Variation, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Mean Variation, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Mean Variation, per cent				
1	Standard condition.....	1140[a]	105	7.9	860[a]	101	6.6	2180[a]	101	6.7	3560	102	3.1	4500	101	6.4		4680[a]	104	4.6
2	Spherical block beneath.....	1050[b]	97	9.8	830[d]	98	7.1	2100[b]	98	5.0	3460	99	6.5	4420	99	6.7		4310[b]	96	7.1
3	Spherical block above and below	1080	100	5.6	870	102	7.9	2180	101	5.6	3440	98	5.3	4450	99	3.1		4480	100	5.3
4	Ball-bearing block on top.....	1050[c]	97	6.4	840[c]	99	6.7	2090[c]	97	4.6	3540	101	3.1	4480	100	3.5		4550[c]	101	8.4
	Av. for all cylinders Ref. 1 to 4	1080[d]	100	8.1	850[d]	100	7.1	2150[d]	100	5.0	3500	100	4.5	4470	100	5.3		4500[d]	100	6.7
5	No spherical block.....	880	81	10.0	780	92	9.7	1890	88	8.2	3120	89	8.9	3860	86	16.2		3870	86	13.2
6	Spherical block off center $\frac{1}{16}$ in.	....	...	...	...	...	...	2160	100	5.9	...	...	...	...	...	...		....	...	...
7	" " " " $\frac{1}{8}$ in.	....	...	...	...	...	...	2140	100	6.2	...	...	...	...	...	...		....	...	...
8	" " " " $\frac{1}{4}$ in.	....	...	...	...	...	...	2150	100	5.0	...	...	...	...	...	...		....	...	...
9	Standard condition, without lower distributing plate....	1060	98	4.6	820	96	7.7	2100	98	5.7	3450	99	5.0	4650	104	2.7		4540	101	4.7
10	Standard condition without lower distributing plate, 300,000-lb. machine.....	1100	102	4.5	930	109	5.9	2220	103	4.4	3650	104	3.8	4460	100	6.9		4480	100	5.5
11	4 by 13-in. steel plate under cylinder, span 23½ in.....	1090	101	8.2	880	103	7.5	2130	99	6.6	3560	102	4.1	4620	103	3.1		4400	98	5.3
12	2⅝ by 8 $\frac{5}{16}$-in. steel plate under cylinder, span 16⅝ in.....	1040	96	8.3	860	101	4.0	2160	100	5.0	3450	99	3.4	4500	101	4.0		4330	96	6.9

[a] Average of 14 to 24 tests.
[b] Average of 15 to 18 tests.
[c] Average of 5 to 8 tests.
[d] Average of 49 to 58 tests.

TABLE 2.—COMPRESSION TESTS OF CONCRETE CYLINDERS USING DIFFERENT METHODS OF CAPPING AND CAPPING MATERIALS—SERIES 179.

6 by 12-in. concrete cylinders. Mix by volume.

Age at test: 28 days.

Relative consistency 1.10 (Flow about 220).

Aggregate: sand and pebbles from Elgin, Ill., graded 0 to 1½ in. (Fineness modulus, 5.65.)

Cement: a mixture of four brands purchased in Chicago.

Cylinders molded on 8-in. cast-iron base plates machined to a plane surface.

Tops of cylinders levelled off with trowel when made.

Cylinders cured in moist room until 3 days prior to test; remainder in air of laboratory.

Cylinders were tested using a 6-in. spherical bearing block carefully centered on top and a 4 by 13 by 24-in. steel distributing plate below.

All tests made on a 200,000-lb. universal testing machine.

Strength-ratio is the ratio, expressed as a percentage, of the strength obtained for a given method of test to the average strength for Ref. 1 to 4 in Table 1 used as the standard of comparison.

Each value is the average of 10 tests made on different days unless otherwise noted.

Reference	End Condition of Test Cylinder	1:7 Mix			1:5 Mix			1:3½ Mix		
		Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Mean Variation, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Mean Variation, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Mean Variation, per cent
1 to 4	Standard of Comparison (see Table 1).....	1080[a]	100	8.1	2150[a]	100	5.0	4500[a]	100	6.7
13	Top trowelled smooth, no capping.....	1040	96	6.4	2020	94	5.9	3620	80	5.7
14	Capped with gypsum 15 min. before test....	1050	97	5.7	2240	104	7.0	4530	101	6.7
15	" " " 30 " " " "	1030	95	4.7	2120	99	7.1	4580	102	5.2
16	" " " 1 hr. " "	1040	96	4.1	2180	101	5.1	4610	103	5.7
17	" " " 3 " " "	1040	96	8.0	2050	95	5.8	4520	100	6.9
18	" " " 6 " " "	1050	97	5.2	2170	101	6.0	4460	99	5.1
19	" " " 24 " " "	1030	95	7.3	2170	101	5.1	4560	101	5.0
20	Cap 1:1 cement and gyp. ½ hr. before test..	1100	102	8.3	2230	104	3.5	4350	97	4.9
21	" " " " " 1 " " " ..	1100	102	6.2	2160	100	7.1	4390	98	7.3
22	" " " " " 3 " " " ..	1110	103	6.8	2160	100	5.7	4370	97	3.6
23	" " " " " 6 " " " ..	1080	100	5.7	2100	98	8.3	4530	100	4.7
24	" " " " " 24 " " " ..	1090	101	5.9	2190	102	4.4	4390	98	8.6
25	" 3:1 " " " 6 " " " ..	1100	102	7.4	2200	102	5.5	4470	99	6.3
26	" 1:3 " " " 6 " " " ..	1090	101	6.4	2120	99	4.8	4580	102	3.4
27	Top ground smooth on grinder.....	1080[b]	100	4.7	2280[b]	106	5.1	4630[b]	103	3.9
28	Capped with beaver board, $\frac{3}{16}$-in. thick.....	1060	98	3.8	2170	101	8.7	4090	91	3.8
29	" " white pine, $\frac{1}{8}$-in. thick.....	990	92	7.3	2120	99	7.3	3920	87	6.5
30	" " millboard, $\frac{1}{16}$-in. thick.....	1090	101	5.7	1970	92	5.7	3780	81	7.7
31	" " leather, $\frac{9}{32}$-in. thick.....	1040	96	5.8	1960	91	6.6	3670	82	8.9
32	" " blotting paper, $\frac{3}{32}$-in. thick....	1000	92	6.3	2080	97	9.0	3470	77	6.2
33	Capped with sheet lead, $\frac{1}{16}$-in. thick.....	1030	95	9.9	1900	88	8.8	3330	74	8.5
34	" " " " $\frac{1}{8}$-in. thick.....	980	91	7.3	1940	90	5.8	3480	74	7.1
35	" " " " $\frac{3}{16}$-in. thick.....	960	89	6.5	1900	88	5.3	3460	77	5.3
36	" " cork carpet, $\frac{5}{16}$-in. thick.....	1010	93	8.1	1870	87	5.9	3140	70	6.5
37	" " sheet rubber, $\frac{1}{16}$-in. thick.....	880	81	9.9	1540	71	6.9	2100	47	7.2
38	" " " " $\frac{1}{8}$-in. thick.....	960	89	7.9	1660	77	11.5	2920	65	12.4
39	" " " " $\frac{1}{4}$-in. thick.....	1010	93	8.7	1710	80	9.5	2820	63	5.6

[a] Average of 49 to 58 tests.
[b] Average of 7 tests.

Table 3.—Compression Tests of Concrete Cylinders with Part of Cap Removed—Series 179.

6 by 12-in. concrete cylinders. Mix by volume.
Age at test: 28 days.
Relative consistency 1.10 (Flow about 220).
Aggregate: sand and pebbles from Elgin, Ill., graded 0 to 1½ in. (Fineness modulus, 5.65.)
Cylinders molded on 8-in. cast-iron base plates machined to a plane surface.
Cylinders capped 4 to 6 hours after making with neat cement (mixed 4 to 6 hours before use); part of cap removed with chisel after 48 hours as indicated.
Cylinders cured in moist room until 3 days prior to test; remainder in air of laboratory
Cylinders tested using a 6-in. spherical bearing block carefully centered on top and a 4 by 13 by 24-in. steel distributing plate below.
Strength-ratio is the ratio, expressed as a percentage, of the strength obtained for a given method to the average strength for Ref. 1 to 4 in Table 1, used as the standard of comparison.
All tests made using a 200,000-lb. universal testing machine.
Each value is the average of 10 tests made on different days unless otherwise noted.

Reference	End Condition of Test Cylinder	1:7 Mix			1:5 Mix			1:3½ Mix		
		Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Mean Variation, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Mean Variation, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Mean Variation, per cent
1 to 4	Standard of Comparison (See Table 1)...	1080[a]	100	8.1	2150[a]	100	5.0	4500[a]	100	6.7
40	Cap removed distance of ¼ in. from edge.....	1130	105	6.8	2160	100	7.6	4540	101	2.3
41	" " " " ½ in. " "	1090	101	5.9	2130	99	5.1	4330	96	3.9
42	" " " " 1 in. " "	1070	99	4.7	2020	94	6.9	4170	93	3.6
43	" " " " 2 in. " "	960	89	6.9	1660	77	11.7	2970	66	10.4
44	Cap removed ¼ in. from edge, replaced with 1:1 cement and gypsum 3 hr. before test..	1110	103	5.9	2150	100	8.1	4560	101	5.0
45	Cap removed ½ in. replaced as in (44).....	1100	102	7.2	2140	100	3.8	4470	99	3.2
46	" " 1 in. " " "	1060	98	3.7	2170	101	4.3	4310	96	6.9
47	" " 2 in. " " "	990	92	6.1	2050	95	5.9	4100	91	7.9

[a] Average of 49 to 58 tests.

Table 4.—Compression Tests of Concrete Cylinders for Miscellaneous End Conditions—Series 179.

6 by 12-in. concrete cylinders, capped 4 to 6 hours after molding, with neat cement (mixed 4 to 6 hours before use). For further details see notes accompanying Table 3.
Each value is the average of 10 tests made on different days unless otherwise noted.

Reference	End Condition of Test Cylinder	1:5 Concrete								
		28 days			3 months			1 year		
		Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Mean Variation, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Mean Variation, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Mean Variation, per cent
1 to 4	Standard of Comparison (See Table 1).	2150[a]	100	5.0	3500	100	4.5	4470	100	5.3
48	Ends concave 0.003 in.....	2190	102	5.5	3580	102	4.0	4480	100	4.2
49	" " 0.1 in.....	1910	89	4.4	2840	81	5.2	3270	73	4.3
50	" " 0.2 in.....	1650	77	6.9	2380	68	4.7	2760	62	5.9
51	Ends convex 0.003 in.....	2210	103	7.0	3620	103	4.9	4620	103	5.5
52	" " 0.1 in	890	41	8.0	1190	34	6.3	1310	29	6.4
53	" " 0.2 in	540	25	10.8	790	23	10.3	880	20	8.0
54	Axis inclined ¼ in.; ends parallel.....	2160	100	5.2	....	....	....	....	....	....
55	" " ½ in.; " "	1980	92	12.9	....	....	....	....	....	....
56	Axis vertical, top inclined ¼ in.....	2200	102	3.3	....	....	....	....	....	....
57	" " " " ½ in.....	2050	95	9.4	....	....	....	....	....	....
58	Standard, except cap wet with water...	2100	98	9.6	....	....	....	....	....	....
59	" " cap coated with cup grease	2100	98	4.9	....	....	....	....	....	....

[a] Average of 58 tests.

TABLE 5.—COMPRESSION TESTS OF CONCRETE CYLINDERS FOR DIFFERENT END CONDITIONS—SERIES 179A.

6 by 12-in. concrete cylinders. Mix by volume.

Age at test: 28 days. Relative consistency 1.10 (Flow about 220).

Aggregate: sand and pebbles from Elgin, Ill., graded 0 to 1½ in. (Fineness modulus, 5.65).

Cement: a mixture of four brands purchased in Chicago

Cylinders molded on 8-in. cast-iron base plates machined to a plane surface unless otherwise noted.

Cylinders capped 4 to 6 hours after making with neat cement (mixed 4 to 6 hours before use) unless otherwise noted.

Cylinders cured in moist room until 3 days prior to test; remainder in air of laboratory.

Cylinders tested using a 6-in. spherical bearing block carefully centered on top and a 4 by 13 by 24-in. steel distributing plate below, except Ref. 102 and 105 to 108.

Strength-ratio is the ratio, expressed as a percentage, of the strength obtained for a given method of test to the strength of similar concrete when tested in accordance with the "Standard Condition."

Each value is the average of 10 tests made on different days.

Reference	End Condition of Test Cylinder	1:7 Mix			1:5 Mix			1:3½ Mix			1:2 Mix		
		Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Mean Variation, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Mean Variation, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Mean Variation, per cent	Compressive Strength, lb. per sq. in.	Strength-Ratio, per cent	Mean Variation, per cent
	Cylinders Capped with Neat Cement When Made												
101	Standard condition	1190	100	3.9	3010	100	4.1	4690	100	4.7	5750	100	3.8
102	Standard; no lower distributing plate	....	...	...	....	...	...	....	...	...	5660	99	4.7
103	Bearing block inverted on top	....	...	...	....	...	...	....	...	...	5770	100	4.5
104	Ball bearing block	....	...	...	....	...	...	....	...	...	5680	99	3.7
105	No bearing block	....	...	...	....	...	...	....	...	...	4720	82	12.1
106	Bearing block off center ⅛ in.	....	...	...	2810	93	8.9	4630	99	5.1	....	...	...
107	" " " " ¼ "	....	...	...	2780	92	7.1	4530	97	4.4	....	...	...
108	" " " " ½ "	....	...	...	2700	90	6.3	4310	92	3.8	....	...	...
109	Axis inclined ¼ in.; ends parallel	....	...	...	....	...	...	4540	97	6.1	....	...	...
110	" " ½ " " "	....	...	...	....	...	...	4430	95	4.2	....	...	...
111	Axis vertical; top inclined ¼ in.	....	...	...	....	...	...	4580	98	6.1	....	...	...
112	" " " " ½ "	....	...	...	....	...	...	4480	96	5.2	....	...	...
	Cylinders Capped with Gypsum in Testing Machine Under Load of 25 lb. per sq. in. for 6 hr. Before Test												
113	Plane base, top trowelled	....	...	...	....	...	...	4630	99	3.9	....	...	...
114	Base convex 0.05 in., smooth	....	...	...	....	...	...	4200	90	4.6	....	...	...
	Cylinders Tested as Made Without Additional Capping or Sheets												
115	¼-in. sheared plate[a], top and	1060	89	5.7	2750	91	6.3	4390	94	3.6	5640	98	4.8
116	" warped " " bottom	950	80	8.7	2300	76	8.3	3580	76	11.8	3900	68	9.2
117	Base convex 0.01 in., top trowelled	990	83	6.6	2390	79	6.7	3210	68	8.6	3630	63	9.0
118	" " 0.02 " smooth	940	79	8.9	2290	76	4.5	2960	63	7.6	3130	54	6.5
119	" " 0.05 "	670	56	6.3	1590	53	6.5	1760	38	10.7	2280	40	10.6
120	Molded on 1-in. pine	980	82	8.8	2440	81	8.8	3190	68	3.7	3860	67	9.1
	Cylinders Tested With Beaver Board Sheets Top and Bottom												
121	¼-in. sheared plate[a], top and	1140	96	5.2	2750	91	6.4	4650	99	5.6	5520	96	3.2
122	" warped " " bottom	1100	92	6.5	2680	89	7.4	4380	94	4.3	5350	93	4.3
123	Base convex 0.01 in., top trowelled	1110	93	5.7	2770	92	6.6	4350	93	2.8	4690	82	4.0
124	" " 0.02 " smooth	1110	93	7.1	2650	88	7.0	4110	88	5.0	4590	80	5.5
125	" " 0.05 "	1050	88	8.5	2250	75	9.0	3500	75	4.2	4130	72	4.3
126	Molded on 1-in. pine	1160	98	4.3	2790	93	4.7	3990	85	7.5	4550	79	5.3

[a] These were the most nearly plane of the sheared plates in the lot.

Table 6.—Compression Tests of Concrete of Different Consistencies for Different End Conditions of Test Cylinder—Series 179*A*.

6 by 12-in. concrete cylinders.
Aggregates: sand and pebbles from Elgin, Ill., graded 0 to 1½ in. (Fineness modulus, 5.65.)
Cement: a mixture of four brands purchased in Chicago.
Age at test: 28 days.
Cylinders capped 4 to 6 hours after mixing with neat cement (mixed 4 to 6 hours before use).
Cylinders cured in moist room until 3 days prior to test; remainder in air of laboratory.
Cylinders tested using a 6-in. spherical bearing block carefully centered on top and a 4 by 13 by 24-in. steel distributing plate below.
All tests made using a 200,000-lb. universal testing machine.
Strength-ratio is the ratio, expressed as a percentage, of the strength obtained for a given method of test to the strength obtained from similar concrete tested in accordance with the standard condition.
Each value is the average of 10 tests made on different days.

Reference	End Condition of Test Cylinder		Relative Consistency of Concrete Mix 1: 3½ by volume.					
			0.90 (.60)[a]	1.00 (.66)	1.10 (.73)	1.25 (.82)	1.50 (.99)	2.00 (1.32)
101	Standard condition.....	Compressive Strength, lb. per sq. in.	5480	5370	4690	3750	2420	1150
		Strength-Ratio, per cent.....	100	100	100	100	100	100
		Mean Variation, per cent.....	5.5	4.7	4.7	8.7	4.8	6.2
127	Molded using ¼-in. warped, sheared steel plates top and bottom; tested without beaver board sheets.	Compressive Strength, lb. per sq. in.	4210	3550	3580	2850	2040	1000
		Strength-Ratio, per cent.....	77	66	76	76	84	87
		Mean Variation, per cent.....	11.1	10.0	11.8	8.9	9.1	13.3
128	Molded using ¼-in. warped, sheared steel plates top and bottom; tested with beaver board sheets top and bottom.....	Compressive Strength, lb. per sq. in.	5210	4850	4380	3590	2180	1190
		Strength-Ratio, per cent.....	95	90	94	96	90	103
		Mean Variation, per cent.....	3.2	4.5	4.3	3.7	6.1	8.1

[a] Water-cement ratio.

Table 7.—Compression Tests of Mortar Used for Capping—Series 179.

2 by 4-in. cylinders.
The mortar was mixed to the consistency ordinarily used in capping concrete cylinders and building units in Laboratory.
The portland cement mortar which stood 6 to 8 hours required additional mixing water before molding cylinders in order to bring it to the same plasticity used for capping.
Each value is the average of 5 tests made on different days.

Capping Material		Mixing Water, per cent by weight of dry materials	Time Mixed Before Molding, hours	Curing Condition	Compressive Strength, lb. per sq. in.									
Cement, per cent by weight	Gypsum, per cent by weight				15 minutes	30 minutes	1 hour	3 hours	6 hours	1 day	2 days	3 days	7 days	28 days
0	100	50	0	Air.....	520	1040	1200	1180	1280	1280	1300	1180	1440	2650
25	75	50	0	Air.....	...	1070	1020	1030	950	1030	1000	1040	1300	2300
50	50	50	0	Air.....	...	540	550	470	470	600	790	900	1180	2160
75	25	40	0	Air.....	...	180	190	180	210	640	890	1170	1720	3010
100	0	33	0	Air.....	...	....	....	....	....	1570	2610	3560	4710	4730
100	0	33	0	Moist Room	...	....	....	....	....	1740	2640	3360	5000	8240
100	0	33	2	Air.....	...	....	....	....	....	1560	2610	3610	4930	4520
100	0	33	2	Moist Room	...	....	....	....	....	1540	2490	3270	4900	8100
100	0	33	4	Air.....	...	....	....	....	....	1490	2790	3690	5000	4690
100	0	33	4	Moist Room	...	....	....	....	....	1560	2540	3530	5340	8650
100	0	34	6	Air.....	...	....	....	....	....	1170	2270	3160	4690	4540
100	0	34	6	Moist Room	...	....	....	....	....	1140	2100	2930	4870	8260
100	0	35	8	Air.....	...	....	....	....	....	860	1880	2770	4210	4120
100	0	35	8	Moist Room	...	....	....	....	....	840	1780	2480	4080	6710

TABLE 8.—TESTS OF CEMENT—SERIES 179 AND 179A.

All tests made in accordance with the Standard Specifications and Tests for Portland Cement of the A.S.T.M.

CHEMICAL ANALYSIS OF CEMENT

Values are the average of 2 tests expressed as percentages by weight.

Cement	Silica, SiO_2	Iron Oxide, Fe_2O_3	Aluminum Oxide, Al_2O_3	Calcium Oxide, CaO	Magnesium Oxide, MgO	Sulfuric Anhydride, SO_3	Loss on Ignition	Insoluble Residue
7153.....	22.42	3.32	5.85	62.10	2.71	1.82	1.15	0.18

MISCELLANEOUS TESTS

Each value is the average of 2 determinations.

Cement	Fineness Residue on No. 200 Sieve, per cent	Water for Normal Consistency, per cent by weight	Time of Setting				Soundness Test (over boiling water)
			Vicat Needle		Gillmore Needle		
			Initial	Final	Initial	Final	
7153.....	18.4	23.5	3 hr. 40 min.	6 hr. 50 min.	5 hr. 25 min.	7 hr. 55 min.	O.K.

STRENGTH TESTS OF 1:3 STANDARD SAND MORTAR

Tension tests of briquettes and compression tests of 2 by 4-in. cylinders.
Specimens cured in water; tested damp.
Each value is the average of 5 specimens made on different days.

Cement	Mixing Water, per cent	Tensile Strength of Briquettes, lb. per sq. in.				Compressive Strength of 2 by 4-in. Cylinders, lb. per sq. in.			
		7 days	28 days	3 months	1 year	7 days	28 days	3 months	1 year
7153.....	10.4	310	405	450	385	1820	2930	3950	4330



FIG. 1.—Standard Method of Capping Cylinders.

6 by 12-in. concrete cylinders molded on plane cast-iron base plates, capped with neat cement which stood from 2 to 6 hours before use and levelled with 8-in. plane cast-iron cover plates.

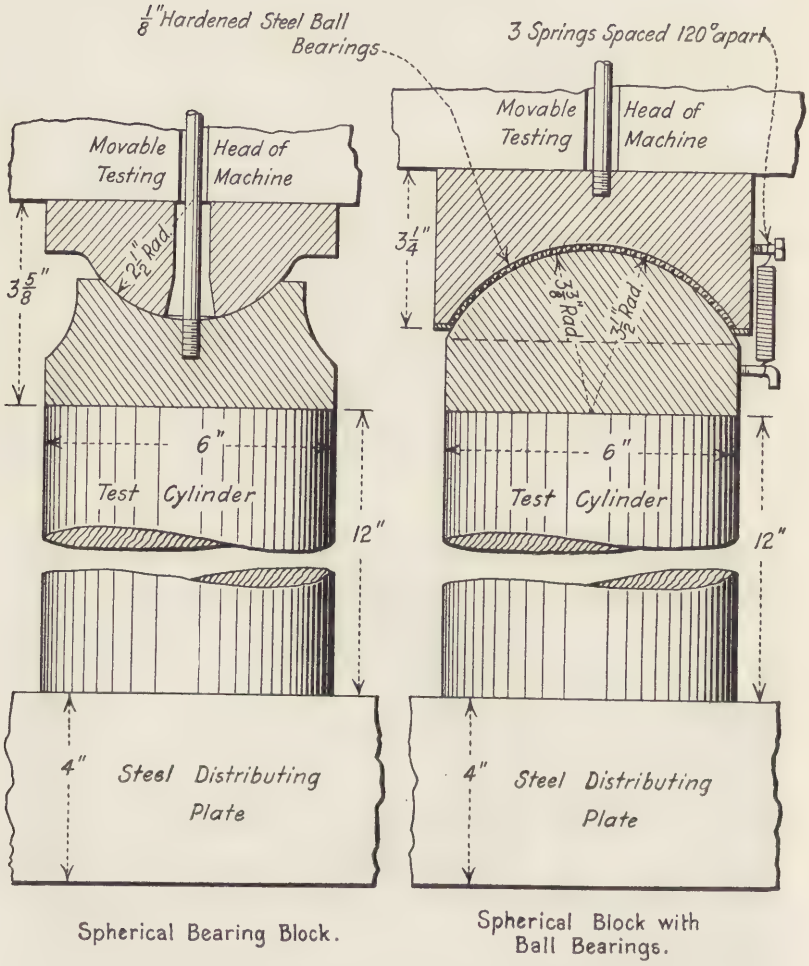


FIG. 2.—Adjustable Bearing Blocks used in Tests.

Steel bearing blocks machined from drop forgings.

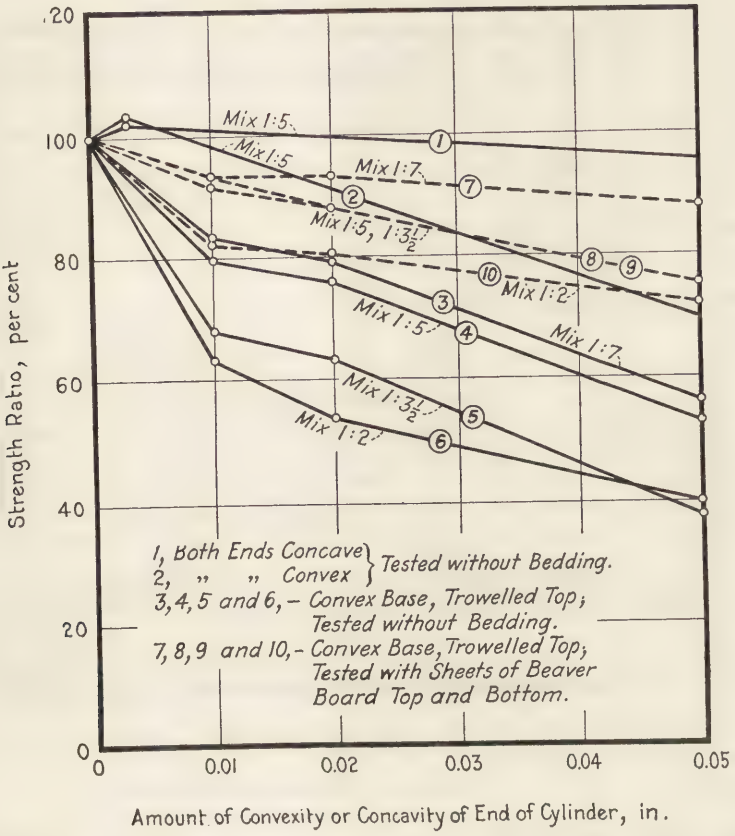


FIG. 3.—Effect of Convexity or Concavity of Cylinder Ends on the Reliability of Compression Tests.

Compression tests of 6 by 12-in. concrete cylinders cured in moist room.
Mix by volume.
Age at test, 28 days.
Each value is the average of 10 tests made on different days.
Data from Tables 4 and 5.

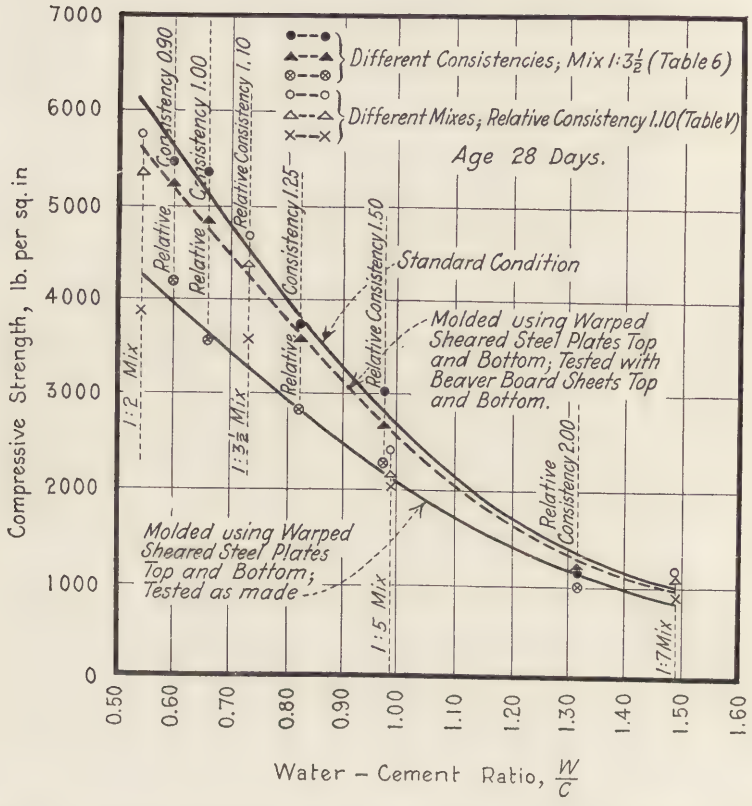


FIG. 4.—Water-Ratio-Strength Relation as Influenced by Condition of Cylinder Ends.

Compression tests of 6 by 12-in. concrete cylinders cured in moist room.
Mix by volume.
Each value is the average of 10 tests made on different days.
Data from Tables 5 and 6.

BIBLIOGRAPHY

The following bibliography gives references to other tests bearing on the same subject The brief notes which are given for several of the references reflect the views expressed therein and do not necessarily indicate the opinion of the author of this report based on a study of the same and later, more complete data.

"Notes on Resistance of Bricks to Crushing Force," by G. S. Greene, Jr., *Journal*, Franklin Inst., Vol. 65, p. 333, 1873.

Tests made on half brick using (1) 2 pieces of board ½ in. thick; (2) a layer of sand; (3) packed with 2 pieces of cigar-box wood; (4) packed with sand.

"Report on Building Stones," Report of Chief of Engineers, U. S. Army' 1875, Appendix II, p. 29.

"Testing Materials of Construction," by W. C. Unwin, Published by Longmans, Green Co., New York, 1888, p. 416.

Discusses the diminution of crushing resistance of stone bedded on lead, and between millboards. The following forms of bedding were used: One plate of lead on each face, three plates of lead on each face, one plate of lead on each face ⅛ in. smaller than face all around, between 2 millboards on each face, and cemented between 2 strong iron plates with plaster of Paris. (Lead plates 0.085 in. thick.)

"Compressive Resistance of Freestone, Brick Piers, Hydraulic Cements, Mortars and Concretes," by Q. A. Gillmore, Published by Wiley & Sons, New York, 1888, p. 2.

Tests made on stones which were of tough, medium and soft texture, using steel, wood, lead and leather for bedding. Values obtained were:

		Steel	Wood	Lead	Leather
Tough		100	94	65	60
Medium		100	82	65	63.5
Soft	Sebastopol limestone	100	100	100	100
	Drab-colored sandstone	100	100	100	.....
	Massillon sandstone	100	110	90	59.4
	Massillon sandstone	100	103	85	.....

"Materials of Construction," by J. B. Johnson, Published by Wiley & Sons, New York, 1914, p. 354.

Capping of specimens recommended with plaster of Paris, using sized paper between capping and specimen to prevent absorption of water by specimen, which reduces strength of the material if it has a high absorption. Small load put on specimen while plaster is soft and left on for 10 min. or longer, until bed is hardened, when test proceeds to failure. Single thickness of tar-board recommended, but no material which will flow (such as lead) or spread (as wood). Ground surfaces also recommended. Graph shows effect of bedding with lead and also with plaster of Paris on strength of concrete.

"Treatise on Masonry Construction," by I. O. Baker, Published by Wiley & Sons, New York, 1899, p. 9.

Relative crushing strengths of pressing surfaces as follows: Steel 100, Wood 89, Lead 65 and Leather 62.

"Spherical Bearings," by M. Schuyler, *Proceedings*, Am. Soc. Testing Mats., Vol. 13, p. 1004, 1913.

Examples of different bearing surfaces shown and discussed.

"Capping for Compression Specimens," by H. D. Foster, *Journal*, Am. Ceramic Soc., Vol. 6, p. 623, May, 1923. *Engineering News-Record*, Vol. 90, p. 1003, June 7, 1923.

Compressive strength tests made on tile capped with unretarded gypsum, with neat portland cement, with mixture of 3 parts by volume of portland cement to 1 part of unretarded gypsum, and on tile whose bearings were ground. Tile whose bearings were ground gave highest results. Results based on workability, yielding of cap, and influence of bearing block.

"Effect of Irregular Ends on Concrete Test Cylinders," by D. V. Terrell, *Engineering and Contracting*, Vol. 60, p. 228, August 1, 1923.

Tests indicate (1) that test cylinders should be 10 in. long; (2) that no attempt be made to finish the ends; (3) that they be capped after they reach the laboratory; (4) that all caps be at least 7 days old.

"Effect of Imperfect Ends on Compressive Strength of Concrete Test Cylinders," by D. V. Terrell, *Kentucky Road Builder*, March, 1923. *Engineering and Contracting*, Vol. 59, p. 984, May, 1923.

Methods of testing 1:2:4 concrete given: (1) concrete with neat cement, cut off with straight-edge and made nearly perfect as possible; (2) finished with trowel leaving uneven ends; (3) sheet lead placed over tops of rough cylinders to take up unconformities in cylinder; (4) Beaver Board used instead of sheet lead; (5) capped with plaster of Paris and placed under 2000-lb. pressure until cap set and then broken. Best results were obtained in the following order: 1, 5, 2, 4, 3.

Bulletin 15

Structural Materials Research Laboratory
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Chicago

Studies of Curing Concrete in a Semi-arid Climate

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Cooperation of the California Highway Commission
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STUDIES OF CURING CONCRETE IN A SEMI-ARID CLIMATE

By Harrison F. Gonnerman and C. L. McKesson

Summary and Conclusions

This investigation of the relative efficiency of various methods of curing concrete was conducted during the summer of 1924 as a co-operative research by the California Highway Commission and the Structural Materials Research Laboratory. Because of the slight probability of rainfall during the summer months, the low relative humidity and the high mean temperature, Sacramento, California was chosen as a site for the experiments. The climatic conditions under which the tests were made were quite unfavorable for the proper curing of unprotected concrete, but are typical of those encountered in semi-arid regions.

The curing experiments were carried out on 7 by 10 by 38-in. plain concrete beams made out-of-doors and cured in the open by the following methods (after removal of forms at 16 to 24 hr.):

(1) Covering with 2 in. earth, wet for 3, 7, 14, 26 and 88 days;
(2) Air curing, no surface treatment;
(3) Covering with asphaltic paper;
(4) Flake calcium chloride, 1½, 2, 2½, 3 and 5 lb. per sq. yd. sprinkled over the surface;
(5) Commercial sodium silicate (41° Baumé); applied with a brush, undiluted, 1 to 1½ and 1 to 3 solutions.

The investigation included transverse tests and tests for surface hardness on five hundred and eighteen 7 by 10 by 38-in. beams and compression tests on one hundred and seventy-five 6 by 12-in. cylinders and prisms. The beams were tested at ages of 3 to 90 days with the cured surface in tension. The surface hardness of the concrete was measured by a ball-indentation test. The cylinders were cured in damp sand and tested at ages of 7 to 90 days. The prisms were cured with wet earth and calcium chloride and tested at 28 days.

The concrete was machine-mixed in the proportion of 1-2.2-3.0 by loose volume, and contained 6 sacks of cement per cubic yard. The consistency of the concrete was about that used in machine-finished concrete pavements (slump of about 1½ in.). A few tests were made with wetter concrete. In 110 beams and 37 cylinders calcium chloride (2% by weight of cement) was used as an admixture.

In comparing the relative efficiency of the curing methods, the strength of concrete cured with earth wet 7 and 14 days (which showed practically identical results) was taken as the standard; the "strength-ratios" for other methods were based on these values. For specimens tested at 3 days the flexural strength for 3-day wet-earth curing was taken as the standard of comparison.

The moduli of rupture of concrete without admixture (average compressive strength at 28 days 4000 lb. per sq. in.) for the different methods of curing in the order of their superiority were:

Method of Curing	Modulus of Rupture of 7 by 10-in. Plain Concrete Beams, lb. per sq. in.					Strength-Ratio per cent				
	3d.	7d.	14d.	28d.	90d.	3d.	7d.	14d.	28d.	90d.
2 in. wet-earth covering applied 16 to 24 hr. after molding and left in place for 7 or 14 days	.....	445	470	535	600	.....	100	100	100	100
2 in. wet-earth covering applied 16 to 24 hr. after molding and left in place for 3 days	340	435	490	505	565	100	98	104	94	94
Beams molded and cured in concrete forms using surface application of calcium chloride, 2½ lb. per sq. yd., placed 16 to 24 hr. after molding and not removed	.....	.....	470	470	535	.....	.....	100	88	89
Covered with asphaltic paper 16 to 24 hr. after molding until 1 day before test (Average for paper on top only and top and bottom)	.....	410	430	470	465	.....	92	91	88	78
Beams molded in wood forms and cured with surface application of calcium chloride, 2½ lb. per sq. yd., placed 16 to 24 hr. after molding and not removed	370	390	410	415	495	109	88	87	78	83
Air curing; no surface treatment	295	345	365	385	435	87	78	78	72	73
Sodium silicate, applied with brush 16 to 24 hr. after molding (Average for undiluted, 1 to 1½ and 1 to 3 solutions)	....	340	355	395	445	....	76	76	74	74

Based on these and other data from the tests, the following conclusions are drawn:

(1) A curing method is efficient which maintains the moisture content of the concrete during the early stages of hydration, about equal to the original mixing water. Wet-earth curing gave the best results of the methods used; this method apparently supplied moisture in sufficient quantity to replace losses due to evaporation and to absorption by subgrade. Curing methods which permitted high evaporation losses gave concrete of low strength.

(2) The tests showed that concrete cured under earth wet for 7 or 14 days was only slightly stronger than when cured under earth wet for 3 days. In view of this and of the small rate of increase in strength after the 14th day it may be concluded that with temperatures no lower than prevailed in these tests (70°F.) concrete pavements cured by covering with wet burlap for 16 to 24 hr. and then with earth kept wet for 7 days, may safely be opened to traffic in 14 days.

(3) Curing with a surface application of flake calcium chloride, 2½ lb. per sq. yd., gave strength-ratios of from 88% at 7 days to 83% at 90 days; with less than this amount and with 3 and 5 lb., there was a slight reduction in strength.

When the calcium chloride was washed off after 3 hr., the strengths were reduced perceptibly; washing off calcium chloride after 1 day gave essentially the same strengths as when left on the surface.

Surface hardness for calcium chloride-cured beams was considerably less than for beams cured with wet earth or with asphaltic paper.

(4) For beams molded and cured in concrete forms using calcium chloride, 2½ lb. per sq. yd., the strength-ratios ranged from 100% at 14 days to 89% at 90 days. The strengths in this case were about 12% higher than for beams molded in wood forms and cured in the standard manner with a similar amount of calcium chloride, that is, on paper with the sides and ends of the beams banked with dry earth.

(5) Asphaltic paper curing gave average strength-ratios ranging from 92% at 7 days to 78% at 90 days; surface hardness was almost as high as for wet-earth curing.

(6) Both air curing and sodium silicate curing showed low strength and surface hardness. The strength-ratios for these methods of curing ranged from about 77% at 7 days to 74% at 90 days.

(7) 2% calcium chloride used as an admixture in the concrete increased the flexural strength about 4% at 3 days for air- and calcium-chloride curing and gave no increase for wet-earth curing. It should be borne in mind that only one percentage of calcium chloride and one brand of portland cement was used. Different cements respond in different degree to calcium chloride as an admixture; furthermore, the high temperatures which prevailed had a favorable influence on early strength and may have minimized the effect of the calcium chloride.

(8) Indentation loads used in measuring surface hardness averaged 21 times the modulus of rupture; the greatest surface hardness was found for concrete of highest flexural strength. This method of test showed that calcium chloride, sodium silicate and air curing produced a more friable surface than wet-earth or paper curing.

STUDIES OF CURING CONCRETE IN A SEMI-ARID CLIMATE

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Introduction

Investigations carried out in recent years by Government, state highway and other research laboratories have demonstrated the necessity of providing concrete with moisture during the early hardening period if high strength and other desirable properties are to be secured. In concrete highway construction, the methods of curing most frequently used are ponding, or covering with earth, straw or other materials kept wet for periods ranging from 7 to 18 days. These methods cannot always be used to advantage, however, on account of cost, scarcity of water or absence of necessary covering materials and are generally impracticable in congested districts.

During the past few years, calcium chloride, a highly deliquescent salt, has been recommended as a curing agent for concrete roads on the theory that when spread over the surface it will attract sufficient moisture from the air to prevent drying of the concrete during early hardening. Sodium silicate brushed over the surface has also been recommended for curing concrete roads. The tests described in this report were made to determine the efficiency of these and other materials compared with earth kept wet for periods ranging from 3 to 88 days.

In the summers of 1923 and 1924, comprehensive series of tests on the curing of concrete beams were made at Lewis Institute. However, due to the abnormal rainfall during the period of curing, the results were inconclusive. It was with a view to eliminating so far as possible the effect of variable weather conditions and to study the curing of concrete in a hot, semi-arid climate, that the tests were made at Sacramento. The tests were carried out during the summer and fall of 1924, in cooperation with the California Highway Commission.

Acknowledgment is made to W. B. Stonebraker, Assistant Testing Engineer of the California Highway Commission, for his valuable aid in making and testing the specimens and in compiling the data.

Outline of Tests

The curing experiments were made on 7 by 10 by 38-in. plain concrete beams. For details of the tests see Table 3. The beams were made out-of-doors June 30 to July 28, 1924. Transverse and surface

hardness tests were made on the beams at ages of 3, 7, 14, 28 and 90 days in the Laboratory of the Commission at Sacramento. This report covers transverse and hardness tests on 518 beams and compression tests on 175 cylinders and prisms.

The beams were cured by the following methods upon removal from the forms after 16 to 24 hr.:

(1) *Earth*—2 in. of earth spread over the beam and wet twice daily for 3, 7, 14, 26 and 88 days;

(2) *Air Curing*—Top of beam exposed to the sun without protection.

(3) *Asphaltic Paper*—An open-textured paper, heavily impregnated with asphaltic material (thickness about $\frac{1}{32}$ in., weight about 26 oz. per sq. yd.) was placed as follows:

(a) on top of beam;

(b) on bottom and top of beam.

(4) *Commercial Flake Calcium Chloride*—1½, 2, 2½, 3 or 5 lb. per sq. yd. spread over top of beam.

A chemical analysis of the calcium chloride showed 72.0% calcium chloride, 0.4% magnesium chloride, 0.8% sodium chloride and 26.7% water of crystallization.

(5) *Commercial Sodium Silicate*—(41° Baumé, $Na_2O:SiO_2$= 1:3.25) applied to top of beam with a brush:

(a) undiluted, one application;

(b) 1 volume silicate to 1½ volumes water, 3 applications;

(c) 1 volume silicate to 3 volumes water, 3 applications.

For several of the curing conditions, concrete containing an *admixture* of 2% calcium chloride by weight of cement was tested.

Ball-indentation tests were made on half beams after the transverse tests to obtain information on the hardness of the cured surface. This test consisted of measuring the load required to embed a ½-in. steel ball in the top of the beam to a depth of ½ its diameter.

In order to check the quality of the concrete, 6 by 12-in. cylinders were made for test in compression at 28 days; a few cylinders were tested at 7, 14 and 90 days.

In addition to the tests outlined above, twenty 7 by 10 by 38-in. beams and twenty 6 by 12-in. prisms were made in the field from the concrete being placed in a pavement near Sacramento. After 1 day in the form, these beams and prisms were removed to the curing yard where they were cured with moist earth until 1 day before test or with calcium chloride and tested at 28 days.

MATERIALS AND TEST PIECES

Cement—Portland cement (A) purchased from dealer's warehouse at Sacramento was used; each of the two lots was from fresh stock (See Table 1).

Aggregate—The fine aggregate was a well-graded, washed sand from Livermore, Calif., ranging in size from 0 to No. 4 sieve. When rodded into a cylindrical measure having a height equal to diameter it weighed dry, 110.3 lb. per cu. ft.; dry sand measured loose weighed 103.5 lb. per cu. ft. The coarse aggregate was washed gravel graded from No. 4 to 1½ in. from Natomas, Calif. Weight 113.6 lb. per cu. ft. dry and rodded, and 105.4 dry and loose. The aggregates were dried in the sun before use; data of tests are given in Table 2.

Mixing Water—The water used for mixing the concrete was from the Sacramento City supply.

Concrete—The cement and aggregates were proportioned by volume, one volume of cement to 4.1 volumes of mixed aggregate measured dry and rodded, which was equivalent to a 1-2.1-2.8 mix by separate volumes, dry and rodded, or 1-2.2-3.0 by volume, dry and loose. This mix required 6 sacks of cement per cubic yard of finished concrete, the minimum permitted by the California Highway Commission Specifications for Concrete Pavements.

The quantities of cement, aggregate and water for each batch were determined by weight. The usual batch consisted of cement, 156 lb.; dry sand, 378 lb.; dry gravel, 522 lb.; and water, 87 lb. The wet concrete weighed about 152 lb. per cu. ft.

Mixing Concrete—The concrete was mixed for 3 minutes in a barrel-type batch mixer of about 6 cu. ft. capacity. (See Fig. 3.) Calcium chloride, when used as an admixture, was dissolved in the mixing water. The concrete was discharged from the mixer onto a water-tight, wooden platform from which it was placed in the forms with shovels.

Consistency of Concrete—The consistency of the concrete was about that generally used in the construction of machine-finished concrete pavements (6.3 gal. of water per sack of cement; water-ratio, ratio of volume of mixing water to volume of cement, 0.84). "Flow" and "slump" tests for workability were made on each batch of concrete before depositing in the forms. The dimensions of the truncated cone used in the flow test were 6¾ in. top diameter, 10 in. bottom diameter, and height 5 in. The base diameter of the mass of concrete after the

test, expressed as a percentage of the original diameter is the flow. The consistency was such as would give a flow of about 150 on the flow table (Fig. 3) using fifteen ½-in. drops in about 10 seconds. The slump corresponding to a flow of 150 was about 1½ in. In a few tests 10 and 25% more mixing water was used (water-ratio 0.93 and 1.05).

Test Pieces—The curing tests were made on plain concrete beams 7 in. deep, 10 in. wide and 38 in. long. The beams were made and cured in the open in a large, exposed yard near the Highway Laboratory (See Fig. 1).

Most of the beams were cast in 5-gang wood molds resting on level wood platforms; both molds and platforms were kept well oiled. The concrete was placed in two layers, each layer being tamped with a light wooden tamper having a 3 by 3-in. face. A blunt-pointed trowel was used to spade the sides and finish the top surface of the beams. As soon as the concrete had begun to set the beams were covered with burlap which was kept wet until the forms were removed after 16 to 24 hr.

Upon removal from the forms the beams were weighed and then placed on the ground on asphaltic building paper (except as noted in Tables 3 and 4) which was extended up the ends of the beams and the sides of the outer two beams of each group (See Fig. 1) and banked with dry earth. As a further precaution against loss of moisture, the longitudinal cracks between adjacent beams were sealed with paraffin, except in the case of beams cured with wet earth or paper. The curing agents were applied as soon as the beams were in place on the ground.

The beams cured with calcium chloride were placed at one end of the curing yard, 200 to 300 ft. from those cured with wet earth. The wet earth covering the tops of beams cured by this means was removed as soon as the period of wetting was over and the tops left exposed to the sun until time of test.

Fifteen beams (Ref. 30) were molded in concrete forms and covered with burlap kept wet 16 to 24 hr. when they were cured in the forms with calcium chloride. The forms were cast on the ground and the bottoms leveled with sand and covered with asphaltic paper before placing the concrete. These forms were made of lean concrete which could readily be broken away when the beams were removed for test (See Fig. 2).

In general, 4 beams and one 6 by 12-in. concrete cylinder for test at 28 days was made from each batch of concrete. From several batches additional cylinders were made for test at 7, 14 and 90 days.

WEATHER CONDITIONS

The weather at Sacramento was clear and hot during July, August, September and October when the tests were made. The prevailing wind was from the south; average velocity about 9 miles per hour. There was some rain in the early part of October when several of the 90-day beams were curing. In order to maintain the desired curing conditions, beams cured by other methods than wet earth were covered with tarpaulins during rain.

The maximum and minimum daily temperatures and relative humidity during the tests, as reported by the Sacramento Station of the U. S. Weather Bureau, are shown in Fig. 5. The average maximum and minimum temperatures were:

	Temperature. °F.			
	July	Aug.	Sept.	Oct. (1 to 22)
Average Max.	88.5	88.3	86.0	70.0
" Min.	55.9	56.2	55.7	51.0

The temperature in the sun, taken 1 ft. above the ground, was about 10° higher than the Weather Bureau temperatures which were taken in the shade at the top of the Postoffice building 106 ft. above ground.

The average daily maximum and minimum temperatures taken with thermometers placed between the beams were as follows:

Method of Curing	Temperature of Beams, °F.							
	July		Aug.		Sept.		Oct. (1 to 22	
	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.
Air, no surface treatment	90	74	93	75	90	74	78	74
Wet earth	74	62	76	65	75	62	61	53
Asphaltic paper, top only	95	80	90	74	83	69	69	61
" " top and bottom	94	79	90	74	83	69	69	61

The relative humidity was highest during the night and early morning and gradually decreased as the temperature rose during the day (See Fig. 6). The average relative humidities reported by the Weather Bureau were:

Hour of Day	Relative Humidity. per cent			
	July	Aug.	Sept.	Oct. (1 to 22)
5 a.m.	76.8	76.1	65.2	80.3
Noon	42.1	41.8	34.9	62.3
5 p.m.	28.8	29.2	24.6	52.0

On several days the relative humidity in the afternoon was less than 20% (Temp. 95 to 105° F.). Fig. 6 shows typical temperatures and humidities for 6 different days in July.

METHODS OF TESTING

Transverse Tests—All beams were removed from the place of curing 1 day before test, weighed and then permitted to dry until tested. The transverse tests were made in a 200,000-lb. universal testing machine with the *cured* surface in tension. The load was applied at the ⅓ points of a 36-in. span; one end rested on a steel roller and the other on a spherical bearing block.

The flexural strength of the concrete was measured by the modulus of rupture (the tensile stress developed by beam action) and calculated from the relation:

$$R = \frac{WL}{bd^2}$$

where R = Modulus of rupture,
W = Total applied load,
L = Span length,
b = Width of beam,
d = Depth of beam.

The beams generally failed near the middle or between the middle and a load point. A record was made of the depth of penetration of the calcium chloride and sodium silicate which was readily observable at the fractured section; note was also made of the extent to which the concrete dried out.

Surface Hardness Tests—After the transverse tests, indentation tests were made on the *cured* surface of the beams by loading a ½-in. steel ball until it was embedded in the concrete a depth of half its diameter or ¼ in. A steel plate, 2¼ in. square and ¼ in. thick, with a hole just large enough to accommodate the ball prevented a penetration greater than ¼ in.* 2 to 4 tests were made on each beam. A 50,000-lb. hydraulic testing machine was used (See Fig. 4).

Compression Tests—The 6 by 12-in. cylinders after 1 day in the molds were cured outdoors in damp sand. They were removed from the sand 1 day before test and permitted to air dry. The 6 by 12-in. concrete prisms from the road job were cured as indicated in Table 6.

The cylinders and prisms were tested in a 200,000-lb. machine. Data are given in Tables 4 to 6 and Fig. 11.

Miscellaneous Tests—Tests were carried out in sun and shade on:

(1) Evaporation of water and of calcium chloride solutions;
(2) Evaporation of water from concrete of different consistencies;
(3) Behavior of flake calcium chloride on non-absorbent surfaces, and on concrete of different consistencies.

*See "Ball Tests Applied to Cement Mortar and Concrete," by R. B. Crepps and R. E. Mills, Bulletin 12, Eng. Exp. Station, Purdue Univ., Lafayette, Ind., May, 1923.

DATA OF TESTS AND DISCUSSION

Tables 1 to 7 give the data of tests; the principal data are given in Tables 3, 4 and 6. The results are shown graphically in Fig. 5 to 13.

Basis of Comparison of Different Curing Methods—The relative merits of the different methods of curing were judged by comparing the flexural strengths as measured by the moduli of rupture and the surface hardness as measured by the indentation loads with those obtained for wet-earth curing at corresponding ages. No wear tests of the concrete were made; investigations carried out by the U. S. Bureau of Public Roads have shown that surface wear under rubber-tired vehicles is not important.* Principal consideration was given to the flexural strength and to beams made from concrete of water-ratio 0.84 without admixture of calcium chloride. As pointed out below, the moduli of rupture of beams cured with 2 in. earth wet 7 and 14 days (Ref. 11 and 7, Table 3) were essentially the same and the average values for these two curing conditions were used as the standard of comparison instead of the values for 14-day wet-earth curing, as was originally intended; for beams tested at 3 days the modulus of rupture for 3-day wet-earth curing (Ref. 13) was used as the basis of comparison. The efficiency of the different methods of curing are compared by their "strength-ratios," that is, the ratios of the moduli of rupture for a given condition to those for the standard condition expressed as percentages.

Wet-Earth Curing—Curing with wet earth gave the best results of the methods used. (See Tables 3 and 4 and Fig. 7, 8 and 9.) The moduli of rupture for curing with earth wet twice daily for 3 to 88 days were as follows:

Ref.	Curing	Modulus of Rupture, lb. per sq. in.					Strength-Ratio, per cent				
		3d.	7d.	14d.	28d.	90d.	3d.	7d.	14d.	28d.	90d.
11	2 in. earth wet 7 days	.....	445	480	530	605	.....	100	102	99	101
7	2 " " " 14 "	.....	.....	460	540	595	.....	.....	98	101	99
	Average (Used as standard of comparison)	.....	445	470	535	600	.....	100	100	100	100
13	2 in. earth wet 3 days	340	435	490	505	565	100	98	104	94	94
31	2 " " " 26 "	.....	.....	.....	510	.....	.....	.....	.....	95	.....
32	2 " " " 88 "	.....	.....	.....	.....	485	.....	.....	.....	.....	81

The values of modulus of rupture taken as the standard of comparison are the average of the values for Ref. 7 and 11; it will be seen that these beams gave essentially the same strengths at the different ages. The modulus of rupture for Ref. 13 at 3 days (340 lb. per sq. in.)

*"Accelerated Wear Tests of Concrete Pavements," by F. H. Jackson and J. T. Pauls; Proc. Am. Soc. for Testing Materials, v. 24, part 2, p. 864, 1924.

was used as the basis of comparison for beams tested at 3 days. The close agreement between the 3-day wetting and the 7- and 14-day should be noted. The maximum difference (at 28 and 90 days) was only 6%.

The modulus of rupture of the 90-day beams cured with earth wet for 88 days was lower than that of beams wet for 3 to 14 days, due, no doubt, to the fact that they were damp when tested; concrete tested in a damp condition is weaker than similar concrete tested dry.

There was a steady increase in modulus of rupture with age of the concrete. Concrete kept wet for 7 days attained 84% of its 28-day strength at 7 days, 91% at 14 days and 114% at 90 days. In view of the close agreement between the strengths for wet-earth curing for 3, 7 and 14 days and of the small gain in strength from 14 to 21 days (about 4%) it would seem that so far as flexural strength is concerned, concrete pavements kept wet for 7 days, when the temperature is 70° F. or higher, might safely be opened to traffic after 14 days instead of after 21 days or more as is usually specified.

The ratios of moduli of rupture of beams to compressive strengths of 6 by 12-in. cylinders from concrete of the same mix and water-ratio, similarly cured in a damp condition were as follows: 7 days, 16%; 14 days, 14%; 28 days, 13%; 90 days, 13%

Air Curing—As might be expected, the lowest moduli of rupture were generally obtained from the beams the top sufaces of which were exposed to the weather (but protected from rain) upon removal from the molds (air curing). The moduli for these beams were:

Ref.	Curing	Modulus of Rupture, lb. per sq. in.					Strength-Ratio, per cent				
		3d.	7d.	14d.	28d.	90d.	3d.	7d.	14d.	28d.	90d.
1	Air Curing	295	345	365	385	435	87	78	78	72	73

Relatively, the increase in strength up to 90 days for air curing was about the same as for moist-earth curing. It is interesting to note that beams kept wet for as short a period as 3 days after removal from the forms gave about 30% higher flexural strength at 90 days than air-cured beams.

Curing with Sodium Silicate—The sodium silicate was applied to the tops of the beams with a brush. It did not penetrate the concrete, but formed a very thin film on the surface which became quite hard after about 5 days. This film did not prevent the beams from drying out; they lost nearly as much moisture as air-cured beams and, when tested, the concrete at the fractured section appeared to be dry.

The strength-ratios for beams cured with undiluted sodium silicate (Ref. 27) were about 75% at all ages; practically the same as those for air-cured beams (Ref. 1). The diluted solutions of silicate (Ref. 28 and 29) gave essentially the same results as the undiluted in both the transverse and hardness tests. Sodium silicate was of no value as a curing agent for concrete in a hot, semi-arid climate.

Curing with Asphaltic Paper—The moduli of rupture for beams with asphaltic paper on top only (Ref. 3, water-ratio 0.84) ranged from 400 at 7 days to 465 lb. per sq. in. at 90 days and lie between those for wet-earth curing and air curing; they correspond closely with the values obtained with calcium chloride, 2½ lb. per sq. yd. (See Fig. 8). Paper top and bottom (Ref. 4, water-ratio 0.84) gave 7% higher moduli of rupture at ages of 7 and 28 days than paper on top only, but at 90 days approximately the same values were obtained. In no case were the moduli of rupture for paper curing as great as for wet-earth curing. The strength-ratios for this method of curing averaged 92% at 7 days and 78% at 90 days.

The ends of the paper and places where laps occurred were covered with dry earth to prevent escape of moisture. When the beams were removed for test at ages up to 28 days, considerable moisture was observed on the lower paper and large drops of water were frequently found on top of the beams, indicating that the moisture removed from the concrete by evaporation was caught and retained by the paper. With paper on top only, there was moisture on top of beam but not underneath. When the beams were taken from the paper after 90 days there were no indications of moisture either on the top of the beam or on the paper; at this age the beams appeared to be well dried out. Apparently the paper prevented premature drying of the concrete, which accounts for the relatively high moduli of rupture at early ages. Table 4 also shows that the loss in weight of beams with paper top and bottom was generally less than that of beams with paper on top only.

Calcium Chloride Curing—Beams Ref. 15 to 26 and 30 were cured with flake calcium chloride spread over the surface. Generally 2½ lb. per sq. yd. was used. This is the quantity usually specified for curing concrete pavements. The moduli of rupture for beams molded in concrete and wood forms and cured with calcium chloride, 2½ lb. per sq. yd., were:

Ref.	Forms	Modulus of Rupture, lb. per sq. in					Strength-Ratios, per cent				
		3d.	7d.	14d.	28d.	90d.	3d.	7d.	14d.	28d.	90d.
17	Wood	370	390	410	415	495	109	88	87	78	83
30	Concrete	.....	.....	470	470	535	.....	.....	100	88	89

The strength-ratio for Ref. 17 was 109% at 3 days, but was less than 100% at later ages and at 90 days was 83%. The strength-ratios for beams molded and cured in concrete forms were higher than for those molded in wood forms at corresponding ages—100% at 14 days and 89% at 90 days.

In general, 2½ lb. per sq. yd. of calcium chloride gave the best results. With less than 2½ lb. and with 3 and 5 lb. there was a slight reduction in strength.

The strength-ratios for beams having the calcium chloride washed off after 3 hr. were essentially the same as for air-cured beams; when washed off after 1 day, the strength-ratios were about the same as when not removed.

Beams placed on wet-earth subgrade and cured with 2½ lb. calcium chloride (Ref. 21) gave essentially the same strength-ratios at 14 and 28 days as beams cured in the standard manner on paper (Ref. 17); beams placed on dry-earth subgrade (Ref. 22) gave lower strength-ratios (almost identical with those for air-cured beams at 14 and 28 days).

Tests of Concrete from Road Job—Table 6 and Fig. 11 give data of tests on 20 beams and 20 prisms made from 10 different batches of concrete sampled during the laying of about 230 lineal ft. of 20-ft. pavement near Sacramento. The same reference numbers are used for the 2 beams and 2 prisms made from each batch sampled. The concrete contained 6 sacks of cement (portland B) per cubic yard, average slump 2.8 in. After one day in the forms, the specimens were removed to the curing yard. Ten of each type of specimen were cured with earth wet twice daily for 26 days and 10 by spreading 2½ lb. flake calcium chloride per sq. yd. over the surface. Immediately after the 28-day transverse tests of the specimens cured by wet earth, one half of each beam was treated with a 1 to 4 solution of sodium silicate applied on each of 3 successive days and exposed to the weather; the other half was exposed to the weather untreated. Surface hardness tests were made after 28 days (age 56 days). See Table 6.

The modulus of rupture at 28 days for wet-earth curing ranged from 365 to 470 and averaged 425 lb. per sq. in.; for calcium chloride curing from 290 to 385 and averaged 350 lb. per sq. in.—82% of wet-earth curing.

The compressive strength of prisms cured with wet earth ranged from 2950 to 3680, average 3420 lb. per sq. in.; for calcium chloride curing from 2070 to 3180, average 2680 lb. per sq. in.—78% of wet-earth curing. About the same strength-ratio was obtained in both

transverse and compression tests which would no doubt have been lower if the specimens cured with wet earth had been permitted to air dry longer before testing.

Further Discussion of Calcium Chloride Curing—These tests afforded an opportunity to study the behavior of calcium chloride as a curing agent in a hot, semi-arid climate. The calcium chloride used was the commercial salt containing about 72% of anhydrous calcium chloride, 27% of water of crystallization, and small amounts of magnesium and sodium chloride.

The action of calcium chloride was influenced greatly by the atmospheric conditions. The moisture attracted, collected in large drops and in general, was not distributed so as to cover the entire surface of the beam. The practice was to brush the moisture taken up by the calcium chloride uniformly over the surface of the beam. On days when the relative humidity was low and temperature high, the calcium chloride deliquesced very slowly; in such cases there was opportunity for considerable drying of the concrete. Moisture was generally attracted during the night when the humidity was high.

Although the data are not definite they indicate that, at a temperature of about 90° F., deliquescence took place very slowly when the relative humidity was lower than about 40%. Even at this relative humidity, evidence of the deliquescence of calcium chloride placed in a metal pan near the beams was not always perceptible.

The moisture attracted to the beam evaporated gradually during the day, but at night moisture was again taken up. In general, little if any moisture was noted on the surfaces of beams 4 days after application of less than 2½ lb. per sq. yd. of calcium chloride. Beams cured with 2½ to 5 lb. were dry after about the 5th day. The moisture disappeared from the surfaces of beams cured in concrete forms as quickly as from beams cured in the standard manner. No difference in action of the calcium chloride was observed for beams of concrete with water-ratios 0.93 and 1.05, as compared with those of water-ratio 0.84.

Auxiliary tests and observation showed that part of the moisture attracted by the calcium chloride was taken from the concrete, but the exact amount taken from this source was not determined.

Measurements of the depth of penetration of the calcium chloride into the concrete were made after the transverse tests. In general, the penetration was about $\frac{1}{16}$ in. In a few cases, penetrations up to $\frac{3}{32}$ in. were observed. Chemical analyses of borings from the beams confirmed the above measurements.

Effect of Quantity of Mixing Water—Forty beams contained 10% and 20 beams contained 25% more mixing water than the usual amount. For curing with earth wet 14 days the modulus of rupture at 14 days was not lowered by the addition of 10 and 25% more mixing water; at 28 days it was reduced 10 and 16% respectively.

Beams containing 10% additional mixing water and cured with paper gave about 4% lower moduli of rupture at 14 days and about 7% lower at 28 days than similarly cured beams containing the usual amount of water. For calcium-chloride curing, beams containing 10 and 25% more than the usual amount of mixing water gave about 7% lower moduli of rupture at 14 days and 15% lower at 28 days.

Calcium Chloride as an Admixture in Concrete—In 110 beams and 37 cylinders, 2% calcium chloride (in terms of weight of cement) was dissolved in the mixing water in order to obtain information on the effect of this percentage of calcium chloride on the flexural strength of the concrete at early ages.

For air-cured and calcium chloride-cured beams containing the 2% admixture, the moduli of rupture at 3 days were about 4% higher than for similarly cured concrete without admixture. Beams containing calcium chloride which were cured by covering with wet earth gave slightly lower strength at 3 days than beams without admixture and similarly cured. Although the data in Table 4 show that there was less evaporation of mixing water from the concrete containing calcium chloride, in these tests the addition of 2% calcium chloride had little if any beneficial effect on early flexural strength. In considering these results it should be borne in mind that only one percentage of calcium chloride and one brand of cement was used; different cements respond in different degree to calcium chloride as an admixture. Furthermore, the high temperatures which prevailed during early curing would tend to increase the early strength of the concrete and thus may have minimized the effect of the calcium chloride. Earlier and more comprehensive tests on different cements by the Structural Materials Research Laboratory* showed about 40% increase in *compressive strength* at 3 days and about 30% at 7 days for an admixture of 2 to 4% calcium chloride in concrete of similar quality.

Age-Strength Relation—Fig. 8 shows the relation between the modulus of rupture of concrete and age for the more important curing conditions. In general, there was an increase in flexural strength with age for all methods of curing; paper top and bottom gave a relatively low strength at 90 days. The following table shows the ratio, for each

*See "Calcium Chloride as an Admixture in Concrete," by Duff A. Abrams; Proc. Am. Soc. for Testing Materials, v. 24, part 2, p. 781, 1924. Bulletin 13, Structural Materials Research Laboratory, Lewis Institute, Chicago.

curing method, of the strength at each age to the 28-day strength obtained by that method; these ratios should not be confused with the strength ratios in Table 3 which, for a given age, are based on the flexural strength of beams cured with earth wet 7 or 14 days at that age:

Ref.	Curing	Flexural Strength, Ratio to 28-day Strength, per cent				
		3d.	7d.	14d.	28d.	90d.
13	2 in. earth wet 3 days	67	86	97	100	112
11	2 " " " 7 "	.....	84	91	100	114
7	2 " " " 14 "	.....	.....	85	100	110
	Average	67	85	91	100	112
3	Asphaltic paper, top only	.....	89	91	100	103
4	" " " and bottom	.....	85	91	100	94
	Average	.....	87	91	100	98
17	Calcium chloride, 2½ lb. per sq.yd.	89	90	99	100	119
30	" " 2½ " " " " (in concrete forms)	.....	.....	100	100	114
	Average	89	90	100	100	116
1	Air curing, no surface treatment	77	90	95	100	113
27	Sodium silicate, undiluted, 1 application	.....	87	91	100	114

The 3- and 7-day flexural strengths were surprisingly high as compared with the 28-day strengths due probably to the high atmospheric temperatures prevailing during the tests which would have a favorable influence on the early strength of the concrete. The percentages of the 28-day strengths were approximately the same at all ages for the different methods of curing except calcium chloride which generally gave higher values than the other methods.

Hardness Tests—Data of indentation tests made to determine the hardness of the *cured* surfaces of the beams are given in Tables 4 and 6 and in Fig. 9 and 10. Comparison of Fig. 8 and 9 shows that the indentation tests gave indications similar to the transverse tests, in that beams which gave highest flexural strength showed the greatest surface hardness. In some instances there appeared to be little if any increase in surface hardness after 14 days.

Beams cured with earth kept wet for different periods withstood higher indentation loads than beams cured by other methods with the possible exception of those cured with paper. The indentation load for beams cured with wet earth ranged from 7500 lb. at 3 days to about 12,000 lb. at 28 and 90 days. The indentation loads for air-cured concrete were much lower than those for wet-earth curing. Beams cured with paper gave indentation loads ranging from 9700 lb. at 7 days to about 10,500 lb. at 28 and 90 days. Beams cured with undiluted sodium silicate gave the lowest indentation loads which ranged from 6900 lb. at 7 days to 8700 lb. at 90 days; the 1 to 3 solution gave somewhat

better results that the 1 to 1½ solution and the undiluted silicate. The average indentation load at 56 days for the beams from the road job (Table 6) which were treated with a 1 to 4 solution of sodium silicate on 3 successive days was about 20% lower than that of untreated beams.

For calcium chloride curing (Ref. 17) the indentation loads ranged from 6500 lb. at 3 days to 9500 lb. at 90 days. These values are lower than those for wet-earth curing and are approximately the same as for air curing.

For the same curing conditions, beams containing 2% calcium chloride admixture, withstood essentially the same indentation loads as beams without admixture.

The indentation load averaged about 21 times the modulus of rupture. Fig. 10 shows that the indentation load increased approximately in proportion to the modulus of rupture.

It was noted that there was considerable variation in the manner in which the ball penetrated the concrete of beams cured by different methods. Beams cured with wet earth and paper generally gave clean-cut indentations and concordant tests, while beams cured with calcium chloride and sodium silicate crumbled and spalled and gave more variable results. The latter two methods of curing produced a more friable surface, particularly at the early ages.

Change in Weight of Beams During Curing—Table 4 gives the change in weight of the beams due to changes in water content during curing. The change in weight is based on the average weight of the beams when removed from forms and 1 day before test, expressed as a percentage of the weight of mixing water.

In Fig. 12 the change in weight of beams made from 1-2.2-3.0 concrete of water-ratio 0.84 without admixture, has been plotted against modulus of rupture. The strength of the concrete bears a well-defined relation to the loss of mixing water during curing. The greater the loss of water the lower the strength. The original mixing water (6.3 gal. per sack of cement) was apparently ample, if not allowed to evaporate, to provide moisture for hydration of the cement, at least through the 90-day curing period.

The efficiency of any curing method may be measured by its ability to prevent the loss of mixing water. Wet curing supplies moisture during the early stages of hydration in sufficient quantity to replace losses due to evaporation and to absorption by subgrade and is, therefore, most efficient. Air-cured beams (Ref. 1) showed greatest losses in weight and greatest reduction in strength. The loss of water for this method of curing ranged from 15% at 3 days to 33% at 90 days.

The loss in water at 90 days was 5.5% for both 7- and 14-day wet-earth curing. Beams which were kept wet for 26 and 88 days showed a gain in water content of 5.7 and 10.4% respectively and gave lower strengths than beams wet only 7 and 14 days and left uncovered in the sun for 82 and 75 days, due, no doubt, to the presence of free moisture in the concrete at time of test. For like conditions of curing, moisture in the concrete at the time of test reduces the strength below that obtained for a specimen which has been dried out before test.*

It is quite likely that specimens wet 26 days and 88 days would show a somewhat higher strength at 1 year or more than specimens wet only 7 and 14 days, provided the latter received no water after the end of the curing period. Such a case does not generally occur in the field as rainfall may be expected to provide moisture necessary for hydration after the expiration of the first 90-day period.

Where early strength is required, as in the case of pavement to be opened to traffic, the tests indicate that such early strength can best be secured by keeping the pavement wet for 7 days and allowing it to dry a few days before opening. Sufficient water will evidently be retained by the concrete during this period, to carry on hydration for at least 90 days. After this time, occasional rainfall will supply moisture for continued hydration which will resume even if retarded by a temporary lack of water as has been shown by previous experiments.†

Miscellaneous Tests—Auxiliary tests were made in order to secure more detailed information on the phenomena involved in the early stages of air and calcium chloride curing. Duplicate tests were made on the change in weight during exposure in sun and shade of metal pans or glass dishes containing the following:

(1) Hydrant water and 1 to 1, 1 to 2 and 1 to 4 solutions of flake calcium chloride;

(2) Flake calcium chloride equivalent to 2½ and 5 lb. per sq. yd.;

(3) 1-2.2-3.0 concrete of water-ratios 0.84, 0.93, 1.05 without covering and covered with flake calcium chloride equivalent to 2½ and 5 lb. per sq. yd.

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*"Relation between Methods of Curing Concrete Test Specimens and their Compressive Strength at 28 Days," by Howard W. Green, Proc. Am. Soc. for Testing Materials, Vol. XIX, 1919, p. 608.

"Saturation of Concrete Reduces Strength and Elasticity," by M. B. Lagaard; Eng. News-Rec., v. 81, p. 1908, Nov. 14, 1918. Cement and Eng. News, v. 31, p. 23, April, 1919.

"Flexural Strength of Plain Concrete," by D. A. Abrams; Proc. Am. Concrete Inst., Vol. XVIII, 1922; Bulletin 11, p. 14, Structural Materials Research Laboratory.

Discussion by F. E. Richart, Proc. Am. Concrete Inst., Vol. XVIII, 1922, p. 47.

"Effect of Saturation on Strength of Concrete," by J. L. Van Ornum; Trans. Am. Soc. Civil Eng., v. 77, p. 438, 1914.

†See "Some Tests on the Effect of Age and Condition of Storage on the Compressive Strength of Concrete," by Harrison F. Gonnerman, Proc. Am. Concrete Institute, 1918, p. 101.

The period of observation was 4 days during which the weight, temperature and humidity were recorded 4 times daily. The tests were repeated during each of 4 weeks and as the results were, on the whole, very consistent, they may be accepted as indicative of the effects under low humidity and high temperature. The shade in this case was provided by a canvas covering over a frame, closed on the sides and open on the ends. Data of the tests are given in Table 7 and Fig. 13.

The evaporation of the fresh water was very high. The average loss in the sun in 4 days from 2000 cc. of water in the pans was nearly 100%; the average loss in the shade was about 65%.

The calcium chloride solutions lost water and the flake calcium chloride took up water until, after about 48 hr., the resulting solutions varied similarly with the changes in temperature and humidity, the solutions containing the smaller amounts of calcium chloride responding more quickly to these changes. (See Fig. 13.)

Concrete of 1-2.2-3.0 mix of water-ratio 0.84 placed in metal pans 13¼ in. in diameter and exposed in sun and shade lost about 30% of its mixing water during the first 3 days of exposure. The rate of loss then rapidly diminished and the total loss in 4 days averaged about 35%. It is probable that most of the remainder of the mixing water was present partly combined in hydrates of definite chemical composition and partly held in loose chemical combination. These tests corroborate the results of the beam tests in which beams air cured for 90 days (Ref. 1) lost only 32.7% of the mixing water. Beams in the main series which were kept wet for 3 days after removal from forms lost only 7.1% of their original water in 86 days of dry-air curing.

From these tests it appears that, in a hot, dry climate unprotected concrete of the quality and consistency used may lose ⅓ or more of the original mixing water, much of this loss occurring in the first few days of exposure. For such concrete, the gain in flexural strength from 3 to 90 days was about 60% of that obtained by wetting for as short a period as 3 days. The tests indicate that if the moisture can be conserved even during the first few days most of the mixing water becomes more or less fixed in the concrete and enough will be provided to carry on hydration for a considerable period. This, together with the higher strength shown by specimens which are tested dry, apparently explains the relatively high strength obtained for specimens cured with earth wet 3 days in this series and in the tests reported by Clemmer and Burggraf.*

*"The Use of Calcium Chloride as a Curing Agent and Accelerator of Concrete," Proceedings, American Soc. for Testing Materials, v. 23, p. 296, 1923.

The 4-day evaporation losses of 1-2.2-3.0 concrete of water-ratio 0.84 exposed in metal pans and covered with flake calcium chloride (Table 7 and Fig. 13) were 11.5% of the water content for the 2½ lb. application and 2% for the 5 lb. application, compared with 35% for concrete without calcium chloride covering. The uncovered concrete continued to lose water with lapse of time. The weight of the calcium chloride covered specimens fluctuated in much the same manner as did the flake calcium chloride exposed in metal pans; the curves in Fig. 13 show a marked similarity.

Calcium chloride on metal took up moisture from the atmosphere by reason of its deliquescent properties. During the hot dry periods of each day it yielded up a portion of the water so acquired. Calcium chloride on the surface of the fresh concrete attracted water in the same manner except that moisture was available from the concrete as well as the air. Although deliquescence took place in varying degrees, the total weight of the specimens continued to decrease. What is believed to be a fairly accurate estimate of the amount of water removed from the concrete by evaporation and by the calcium chloride can be made by assuming that at any period after say, 24 hr., the calcium chloride on the concrete contained the same quantity of water as the calcium chloride exposed in metal pans. On this basis the loss in water from the concrete is the loss in weight of the specimen (concrete and calcium chloride covering) plus the quantity of water held by the calcium chloride (assumed to be same as obtained in the tests of flake calcium chloride exposed in metal pans). The net changes plotted in Fig. 13 were calculated by this method. Fig. 13 shows that there was a gradual decrease in the net water content of the concrete under calcium chloride, totaling about 20% at 4 days. The water which had been taken up by the calcium chloride was present on the surface only; the body of the concrete was, therefore, in the same condition as if it had been air-dried.

The failure of calcium chloride curing to show efficiency even equal to 3-day wet earth curing (in a hot, dry climate) may be understood if, as these tests indicate, a considerable amount of the mixing water is removed from the concrete by the calcium chloride during the early stages of the curing period.

As has been stated, the main series of tests and the auxiliary tests were conducted under severe conditions as to humidity and temperature. Fig. 13 shows average relative humidity and temperature during the 4 weeks in which the auxiliary tests were under way.

TABLE 1.—TESTS OF CEMENT

Portland cement (A) purchased in Sacramento. Lot 1 purchased June 30; Lot 2 July 23, 1924. 93% of specimens were made from Lot 1.

Tests made at Lewis Institute in accordance with the Standard Specifications and Tests for Portland Cement of the American Society for Testing Materials.

CHEMICAL ANALYSIS

Each value is the average of 2 analyses.

Lot	Silica (SiO_2)	Iron Oxide (Fe_2O_3)	Aluminum Oxide (Al_2O_3)	Calcium Oxide (CaO)	Magnesium Oxide (MgO)	Sulphuric Anhydride (SO_3)	Loss on Ignition	Insoluble Residue
1	20.12	4.01	6.45	63.16	1.04	1.59	2.63	0.19
2	20.10	4.25	6.45	63.20	1.03	1.68	2.92	0.20

MISCELLANEOUS TESTS

Each value is the average of 2 tests.

Lot	Fineness Residue on 200-Mesh Sieve	Normal Consistency, per cent by weight	Time of Setting				Soundness Test (over boiling water)
			Vicat Needle		Gillmore Needle		
			Initial hr. min.	Final hr. min.	Initial hr. min.	Final hr. min.	
1	19.8	23.5	4 00	7 50	5 40	9 30	O.K.
2	20.0	24.0	3 40	7 50	5 30	9 50	"

COMPRESSION TESTS OF 1-3 STANDARD SAND MORTAR

2 by 4-in. cylinders cured in water; tested damp.
Each value is the average of 5 tests made on different days.

Lot	Mixing Water, per cent	Compressive Strength, lb. per sq. in.				
		1d.	3d.	7d.	28d.	1 yr.
1	10.5	560	1690	2950	4110	4840
2	10.5	560	1570	2690	4000	4610

TABLE 2.—TESTS OF AGGREGATES

SIEVE ANALYSIS

Each sieve analysis is the average of 10 samples taken on different days during making of beams.

Number or Size of Sieve	Size of Square Opening, inches	Amount Coarser than Each Sieve, per cent by weight		
		Sand	Pebbles	Mixed Aggregate, as Used
100	.0058	96	100	98
48	.0117	86	100	94
28	.0232	67	100	86
14	.046	43	100	76
8	.093	16	99	64
4	.185	0	98	56
⅜ in.	.37	0	93	54
¾ in.	.75	0	63	36
1½ in.	1.5	0	2	1
Fineness Modulus*		3.08	7.55	5.65

*Sum of the percentages in the sieve analysis, divided by 100.

MISCELLANEOUS TESTS

Test	Sand	Pebbles	Mixed Aggregate
Unit weight, dry and rodded—lb. per cu. ft	110.3	113.6	132.5
" " dry and loose—lb. per cu. ft	103.5	105.4	.....
Colorimetric, for organic impurities	Trace	.....	.....
Silt, per cent by weight	1.6	.....	.....

TABLE 3.—MODULUS OF RUPTURE OF CONCRETE BEAMS CURED UNDER DIFFERENT CONDITIONS

Transverse tests of 7 by 10 by 38-in. beams loaded at ⅓ points of 36-in. span.

Mix 1-4.1 by volume (1-2.2-3.0 mix by separate volumes, aggregates dry and loose).

Aggregates: sand and pebbles graded 0-1½ in. (F.M. = 5.65).

Cement: portland (A) purchased in Sacramento.

Consistency: about that used in construction of machine-finished concrete pavements. (Flow about 150, slump about 1½ in.). For a few conditions, 10 and 25 per cent more water used.

Machine-mixed concrete, 4 beams to a batch.

Beams, except Ref. 30, molded in oiled wood forms and covered with burlap kept wet until forms were removed after 16 to 24 hr. when they were placed on ground on asphaltic building paper unless otherwise noted and cured as indicated. Ref. 30 beams were molded and cured in concrete forms. In all cases the beams were removed from ground 1 day before test and permitted to dry.

Strength-ratio is the ratio, expressed as a percentage, of the modulus of rupture for a given method of curing to the average of the values for 2 in. earth wet 7 and 14 days.

In general, each value is the average of 5 tests.

See Fig. 7, 8, 10 and 12.

Ref.	Method of Curing	Water-Ratio	Flow, per cent	Slump in.	Modulus of Rupture, lb. per sq. in. 3d.	7d.	14d.	28d.	90d.	Strength-Ratio, per cent 3d.	7d.	14d.	28d.	90d.
11	2 in. earth, wet 7 days	.84	147	1.6	.....	445[1]	480	530	605	.....	100	102	99	101
7	2 " " " 14 "	.84	146	1.5	.....	.....	460[1]	540	595	.....	.....	98	101	99
	Average	.84	146	1.6	.....	445	470	535	600	.....	100	100	100	100
13	2 in. earth, wet 3 days	.84	149	1.6	340[1]	435	490	505	565	100[4]	98	104	94	94
14[2]	2 " " " 3 "	.83	157	2.3	330[1]	385	435	485	540	97	86	93	91	90
12[2]	2 " " " 7 "	.83	154	2.1	.....	340[1]	445	480	525	.....	76	95	90	88
8[2]	2 " " " 14 "	.83	161	2.6	.....	.....	370[1]	445	545	.....	.....	79	83	91
9	2 " " " 14 "	.93	178	5.2	.....	.....	475[1]	475	.....	.....	.....	101	89	.....
10	2 " " " 14 "	1.05	214	7.9	.....	.....	475[1]	460	.....	.....	.....	101	86	.....
31	2 " " " 26 "	.84	144	1.6	.....	.....	.....	510	.....	.....	.....	.....	95	.....
32	2 " " " 88 "	.84	143	1.5	.....	.....	.....	.....	485	.....	.....	.....	.....	81
1	Air curing, no surface treatment	.84	142	1.4	295	345	365	385	435	87	78	78	72	73
2[2]	" " " " "	.83	156	2.4	310	340	365	400	470	91	76	78	75	78
3	Asphaltic paper, top only	.84	150	1.5	.....	400	410	450	465	.....	90	87	84	78
5	" " " "	.93	175	5.0	.....	.....	405	425	.....	.....	.....	86	79	.....
4	" " " and bottom	.84	153	2.0	.....	415	445	490	460	.....	93	95	92	77
6	" " " " "	.93	175	5.0	.....	.....	415	450	.....	.....	.....	88	84	.....
15	1½ lb. calcium chloride per sq. yd.	.84	149	1.7	.....	.....	380	410	.....	.....	.....	81	77	.....
16	2 lb. " " " "	.84	147	1.6	.....	365	370	415	.....	.....	82	79	78	.....
17	2½ lb. " " " "	.84	150	1.6	370	390	410	415	495	109	88	87	78	83
18[2]	2½ lb. " " " "	.82	153	2.1	380	400	395	435	515	112	90	84	81	86
30	2½ lb. calcium chloride per sq. yd. in concrete forms	.84	146	1.5	.....	.....	470	470	535	.....	.....	100	88	89
19	2½ lb. calcium chloride per sq. yd.; washed off after 3 hr	.84	149	1.7	.....	.....	380	390	.....	.....	.....	81	73	.....
20	2½ lb. calcium chloride per sq. yd.; washed off after 1 day	.84	152	1.5	.....	390	395	415	515	.....	88	84	78	86
21	2½ lb. calcium chloride per sq. yd.; wet earth subgrade	.85	152	1.5	.....	.....	415	445	.....	.....	.....	88	83	.....
22	2½ lb. calcium chloride per sq. yd.; dry earth subgrade	.85	152	1.7	.....	.....	375	390	.....	.....	.....	80	73	.....
23	2½ lb. calcium chloride per sq. yd.	.93	181	5.5	.....	.....	375	360	.....	.....	.....	80	67	.....
24	" " " " " "	1.05	214	7.9	.....	.....	390	350	.....	.....	.....	83	65	.....
25	3 lb. " " " "	.84	143	1.5	.....	410	405	405	.....	.....	92	86	76	.....
26	5 lb. " " " "	.84	147	1.5	.....	395	400	410	450	.....	89	85	77	75
27	Sodium silicate undiluted (1)[3]	.85	156	1.7	.....	340	355	390	445	.....	76	76	73	74
28	Sodium silicate diluted with 1½ parts water (3)[3]	.84	153	1.8	.....	.....	350	385	.....	.....	.....	74	72	.....
29	Sodium silicate diluted with 3 parts water (3)[3]	.84	153	1.8	.....	.....	355	405	.....	.....	.....	76	76	.....

[1]Beams were actually under wet-earth covering 2 days less time than stated under method of curing.

[2]2 per cent calcium chloride by weight of cement used as an admixture in the concrete.

[3]Number of applications of sodium silicate in parentheses.

[4]Strength-ratios for beams tested at 3 days based on modulus of rupture for Ref. 13 at 3 days.

Table 4.—Surface Hardness and Change in Weight of Beams and Compressive Strength of Cylinders

Indentation tests for surface hardness made on cured surfaces of beams using ½-in. steel ball.
Compression tests of 6 by 12-in. concrete cylinders cured in damp sand until 1 day before test.
Average weight of test beams was about 240 lb.
In general each value for indentation load is the average of 10 to 20 determinations; for compression, 3 to 9 tests.
For further details see notes accompanying Tables 3 and 5.
See Fig. 7, 9, 10, 12 and Table 5.

Ref.	Concrete Beams: Method of Curing	Water-Ratio	Change in Weight 1 Day Before Test, per cent of mixing water: 3d.	7d.	14d.	28d.	90d.	Hardness Test Indentation Load, pounds: 3d.	7d.	14d.	28d.	90d.	Cyl's. Comp. Str., lb. per sq. in. 28d.
11	2 in. earth, wet 7 days	.84	.....	+ 6.6[1]	— 3.3	— 4.9	— 5.5	.....	9100[1]	10700	10200	10800	4000
7	2 " " " 14 "	.84	.....	.....	+ 5.5[1]	0	— 5.5	.....	.....	11400[1]	12800	11100	4010
	Average	.84	.....	+ 6.6	+ 1.1	— 2.4	— 5.5	.....	9100	11000	11500	11000	4000
13	2 in. earth, wet 3 days	.84	+ 3.3[1]	+ 1.6	— 4.4	— 8.7	— 7.1	7500[1]	9200	10700	10400	9900	4040
14[2]	2 " " " 3 "	.83	+ 5.5[1]	+ 3.8	— 0.5	— 5.5	— 2.7	7000[1]	10300	10700	10300	10200	3540
12[2]	2 " " " 7 "	.83	.....	+ 5.5[1]	+ 1.6	— 5.5	+ 4.4	.....	8600[1]	10700	11500	10800	3740
8[2]	2 " " " 14 "	.83	.....	.....	+ 6.6[1]	0	0	.....	.....	11200[1]	11100	10700	3720
9	2 " " " 14 "	.93	.....	.....	+ 8.0[1]	— 2.5	.....	.....	.....	9600[1]	10600	.....	3420
10	2 " " " 14 "	1.05	.....	.....	+ 5.0[1]	— 7.7	.....	.....	.....	8800[1]	9600	.....	3180
31	2 " " " 26 "	.84	.....	.....	.....	+ 5.7	.....	.....	.....	.....	11900	.....	4020
32	2 " " " 88 "	.84	.....	.....	.....	.....	+10.4	.....	.....	.....	.....	12000	4080
1	Air curing, no surface treatment	.84	—15.2	—18.0	—22.8	—27.2	—32.7	6600	7700	7400	7400	8800	4000
2[2]	" " " " "	.83	— 7.2	—12.7	—14.3	—20.3	—16.5	7400	7500	8800	9000	8700	3850
3	Asphaltic paper, top only	.84	.....	—11.5	—11.5	—14.8	—14.3	.....	9800	10100	11100	9900	4110
5	" " " " "	.93	.....	.....	— 8.9	—11.4	.....	.....	.....	9700	10200	.....	3680
4	" " " " and bottom	.84	.....	— 6.6	— 6.6	— 9.9	—15.3	.....	9700	10500	11000	10100	3860
6	" " " " " "	.93	.....	.....	— 6.4	— 7.9	.....	.....	.....	9000	10500	.....	3680
15	1½ lb. calcium chloride per sq.yd.	.84	.....	.....	—20.2	—21.8	.....	.....	.....	8000	8200	.....	4280
16	2 " " " " "	.84	.....	—15.3	—18.6	—21.3	.....	.....	7800	8000	8400	.....	3980
18[2]	2½ " " " " "	.84	— 9.3	—15.3	—20.7	—21.9	—21.3	6500	7700	8000	8200	9500	4000
30	2½ lb. calcium chloride per sq. yd. in concrete forms	.82	— 2.2	— 7.1	— 9.3	—15.3	—12.6	6500	7800	7800	8200	7900	3620
19	2½ lb. calcium chloride per sq. yd. washed off after 3 hr	.84	.....	.....	.....	.....	.....	.....	.....	8400	9100	7400	3790
20	2½ lb. calcium chloride per sq. yd. washed off after 1 day	.84	.....	.....	—17.0	—21.3	.....	.....	.....	7800	8300	.....	4280
21	2½ lb. calcium chloride per sq. yd. wet earth subgrade	.84	.....	—13.7	—17.0	—21.3	—19.7	.....	8100	8800	9100	8500	3970
22	2½ lb. calcium chloride per sq. yd. dry earth subgrade	.85	.....	.....	—16.4	—14.8	.....	.....	.....	8000	8500	.....	3780
23	2½ lb. calcium chloride per sq.yd.	.85	.....	.....	—17.5	—19.2	.....	.....	.....	7700	8100	.....	3790
24	2½ " " " " "	.93	.....	.....	—20.5	—26.0	.....	.....	.....	7600	7800	.....	3420
25	3 " " " " "	1.05	.....	.....	—19.9	—27.1	.....	.....	.....	6600	7900	.....	3180
26	5 " " " " "	.84	.....	—13.6	—16.9	—20.8	.....	.....	7800	8600	7800	.....	4070
		.84	.....	—15.9	—17.0	—18.6	—21.4	.....	7000	7800	8400	7700	3800
27	Sodium silicate undiluted (1)[3]	.85	.....	—18.6	—19.7	—22.9	—18.6	.....	6900	6500	8000	8700	3910
28	Sodium silicate diluted with 1½ parts water (3)[3]	.84	.....	.....	—21.3[4]	—25.1	.....	.....	.....	6700	7100	.....	4170
29	Sodium silicate diluted with 3 parts water (3)[3]	.84	.....	.....	—19.6	—25.1	.....	.....	.....	8400	8800	.....	4170

[1]Beams were actually under wet-earth covering 2 days less time than stated under method of curing.
[2]2 per cent calcium chloride by weight of cement used as an admixture in the concrete.
[3]Number of applications of sodium silicate in parentheses.

Table 5.—Average Compressive Strength of Concrete

Compression tests of 6 by 12-in. cylinders made from different batches of concrete used in beams; cylinders molded in cardboard molds placed on plane cast-iron base plates.
In general, cylinders were capped with neat cement 3 or 4 hr. after molding.
Forms removed after 1 day and cylinders cured in moist sand outdoors until 1 day before test.
Cylinders tested in a 200,000-lb. testing machine using spherical bearing block underneath.
Values in parentheses are the number of cylinders tested at each age and in general represent the number of different batches sampled.
For further details, see notes accompanying Table 3.

Water-Ratio	Flow, per cent	Slump, in.	Compressive Strength, lb. per sq. in.: 7d.	14d.	28d.	90d.
.84	149	1.6	2720 (8)	3420 (7)	4000 (65)	4010 (6)
.83	155	2.3	2720 (5)*	3340 (5)*	3780 (23)*	4380 (4)*
.93	176	5.0	2730 (4)	2320 (4)	3560 (9)	4190 (3)
1.05	214	7.9	1860 (1)	2640 (2)	3290 (7)	3820 (2)

*2 per cent calcium chloride by weight of cement mixed with concrete.

TABLE 6.—TESTS OF CONCRETE BEAMS AND PRISMS MADE ON ROAD JOB

Transverse and indentation tests of 7 by 10 by 38-in. beams.
Compression tests of 6 by 6 by 12-in. prisms.
Age at test, 28 days, unless otherwise noted.
Cement: portland B.
Aggregate: sand and pebbles graded 0-2 in.
Mix: 1-1.9-3.4 by loose volume (aggregates damp); 6 sacks of cement per cu. yd. of concrete.
Machine-mixed concrete (10-sack batch); mixed 1½ min. after all materials were in drum.
Beams and prisms cast in oiled, wood forms; forms removed after 1 day and specimens cured as indicated.
Each value is the average of 10 tests.
Strength-ratio is the ratio of the strength for calcium chloride curing to wet-earth curing expressed as a percentage.
See Fig. 11.

Slump, in.	Beams						Prisms				
	Weight, pounds			Modulus of Rupture		Indentation Load, pounds	Weight, pounds			Compressive Strength	
	Form Off	At Test	Diff.	lb. per sq. in.	Strength-Ratio, per cent		Form Off	At Test	Diff.	lb. per sq. in.	Strength-Ratio, per cent
Cured with 2 in. earth wet twice daily for 26 days											
2.8	242.2	243.7	+1.5	425	100	14400* 11700**	38.7	38.8	+.1	3420	100
Cured with flake calcium chloride, 2½ lb. per sq. yd.											
2.8	240.7	238.0	—2.7	350	82	9100	38.9	38.3	—.6	2680	78

*Half beams air cured after 28-day transverse tests and tested at age of 56 days.
**Half beams treated with 1 to 4 solution of sodium silicate on 3 consecutive days after 28-day transverse tests and tested at age of 56 days.

TABLE 7.—CHANGE IN WEIGHT OF CONCRETE, FLAKE CALCIUM CHLORIDE AND SOLUTION OF CALCIUM CHLORIDE EXPOSED TO WEATHER

Concrete: 1-2.2-3.0 mix by loose volume; water-ratio 0.84; exposed in sun in 13¼-in. diameter metal pan.
Flake calcium chloride and 1 to 1 solution of calcium chloride exposed in sun in 13¼-in. diameter metal pan.
Each value is the average of 4 duplicate tests made during 4 successive weeks.
Minus sign indicates a loss and plus sign a gain in weight.
Tests made Aug. 19 to Sept. 13, 1924.
See Fig. 13.

Day	Time	Temperature, °F.	Relative Humidity, per cent	Change in Weight, per cent of flake calcium chloride			Change in Weight of Concrete, per cent of mixing water				
				Calcium Chloride Solution	Flake Calcium Chloride		Without Covering	Covered with Flake Calcium Chloride			
					2½ lb. per sq. yd.	5 lb. per sq. yd.		2½ lb. per sq. yd.		5 lb. per sq. yd.	
								Total	Net	Total	Net
1	9:00 a.m.	76	59	0	0	0	0	0	0	0	0
	11:00 a.m.	88	44	—11.6	0	+ 2.0	— 8.1	+ 0.2	+ 1	+ 1.5	+ 1
	1:00 p.m.	93	34	—23.6	+ 2.4	+ 1.8	—18.1	— 5.0	— 5	— 1.7	— 2
	3:30 p.m.	94	33	—33.6	+ 2.9	+ 2.1	—21.9	— 6.9	— 8	— 2.7	— 5
2	9:00 a.m.	74	54	—23.6	+62.0	+43.0	—25.0	— 3.1	—14	+ 7.7	— 7
	11:00 a.m.	91	34	—33.8	+39.0	+35.0	—25.9	— 6.8	—13	+ 0.6	—12
	1:00 p.m.	98	22	—47.0	+28.0	+26.0	—28.3	— 9.2	—14	— 4.5	—14
	3:30 p.m.	98	22	—57.2	+28.0	+27.0	—28.6	—10.1	—14	— 6.1	—16
3	9:00 a.m.	76	47	—48.2	+61.0	+52.0	—29.5	— 7.6	—18	— 0.8	—19
	11:00 a.m.	92	31	—53.4	+41.0	+43.0	—30.2	—10.1	—16	— 4.5	—20
	1:00 p.m.	98	26	—64.2	+29.0	+30.0	—30.8	—12.5	—17	— 8.8	—19
	3:30 p.m.	100	23	—68.8	+28.0	+28.0	—32.0	—13.7	—18	—10.1	—20
4	9:00 a.m.	73	51	—54.4	+78.0	+60.0	—32.4	— 9.6	—23	— 2.2	—24
	11:00 a.m.	89	42	—59.4	+51.0	+50.0	—32.7	—12.5	—21	— 6.8	—24
	1:00 p.m.	95	30	—66.0	+30.0	+35.0	—33.2	—14.9	—18	—10.7	—23
	3:30 p.m.	97	27	—68.6	+28.0	+31.0	—34.2	—15.5	—20	—11.4	—22
5	8:30 a.m.	73	52	—49.4	+97.0	+73.0	—34.6	—11.5	—28	— 1.5	—27



FIG. 1.—General View of Curing Yard at Sacramento, Calif.

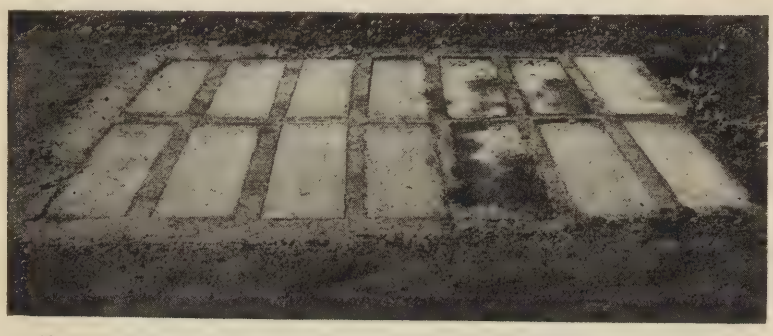


FIG. 2.—View of Beams Molded and Cured in Concrete Forms.

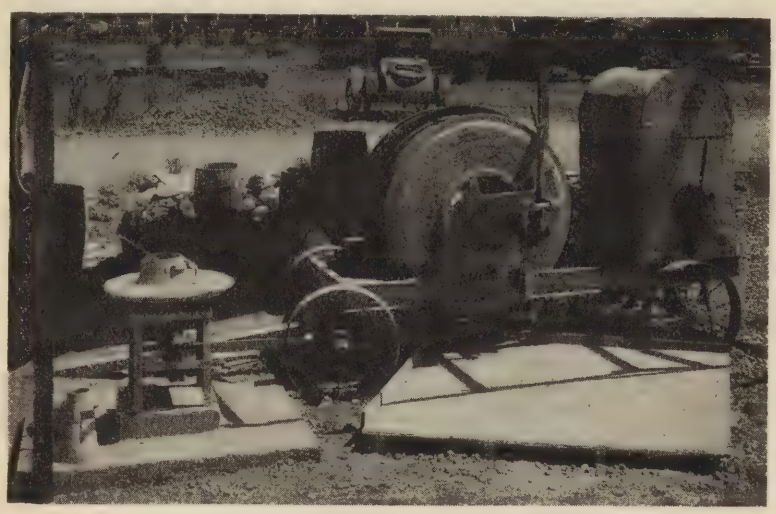


FIG. 3.—Concrete Mixer and Flow Table.



FIG. 4.—Hydraulic Testing Machine Used in Making Surface Hardness Tests of Concrete.

Note the ½-in. steel ball between movable head of testing machine and surface of beam.

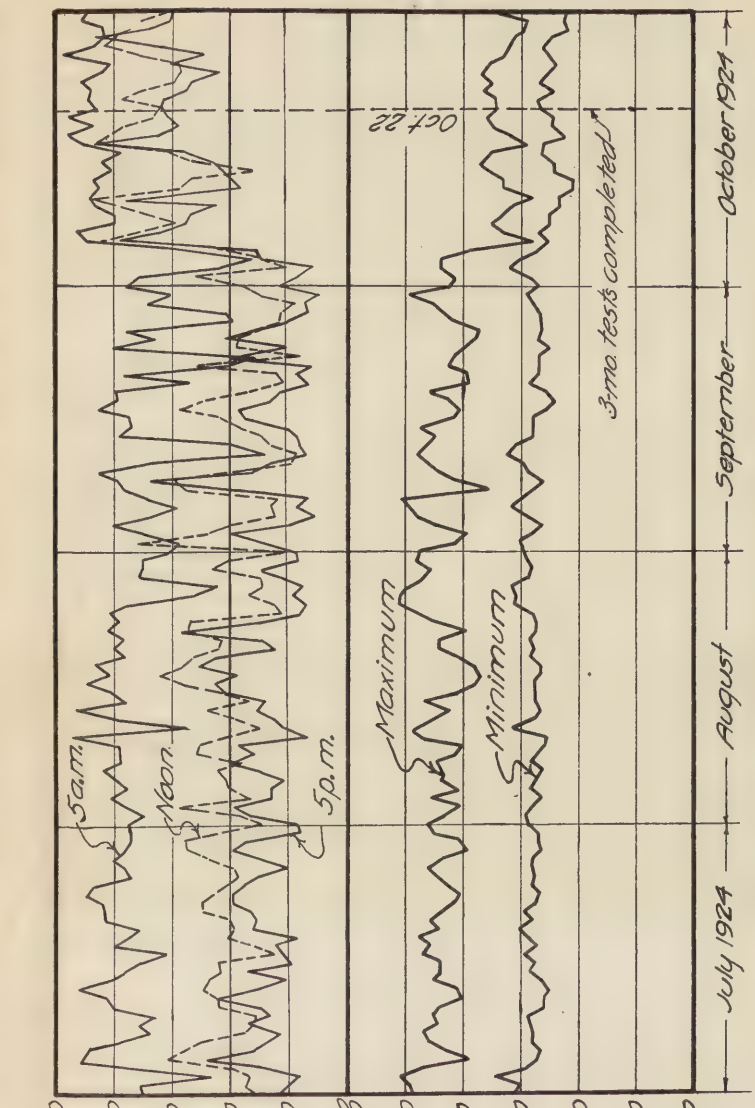


FIG. 5.—Atmospheric Temperature and Relative Humidity.

Data from the Monthly Meteorological Summary of the Sacramento Station, U. S. Weather Bureau.

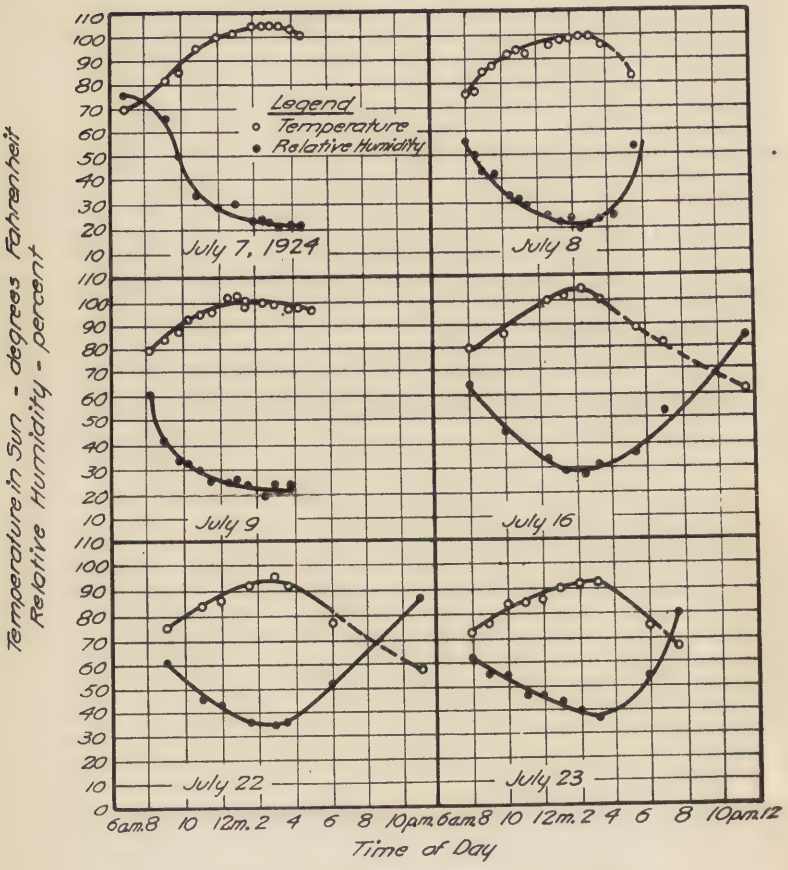


FIG. 6.—Typical Daily Temperatures and Humidities.
Data from observations made at curing yard.

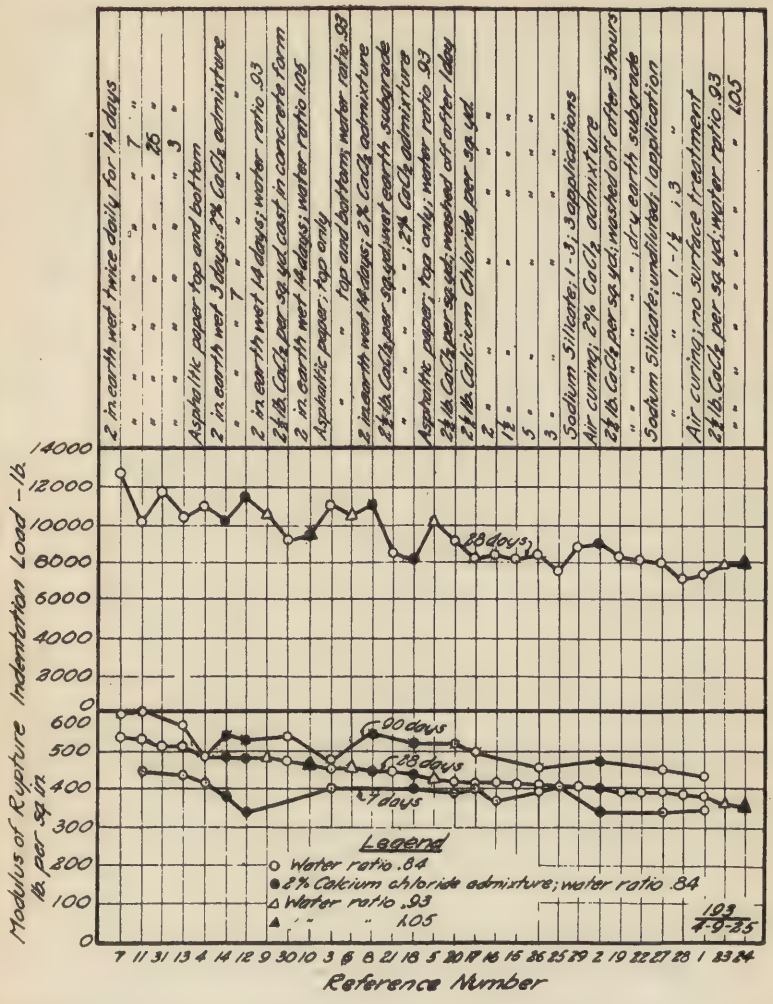


FIG. 7.—Effect of Method of Curing on Modulus of Rupture and on Surface Hardness as Measured by Indentation Load.

Transverse tests of 7 by 10 by 38-in. plain concrete beams loaded at 1/3 points of 36-in. span.

Indentation tests for hardness made on cured surface of half beam after transverse test, using ½-in. steel ball.

In general each value for modulus of rupture is the average of 5 tests; for indentation load, from 10 to 20 determinations.

Data from Tables 3 and 4 plotted in order of descending values of modulus of rupture at 28 days.

Modulus of rupture at 3 and 14 days and indentation loads at 3, 7, 14, and 90 days not shown.

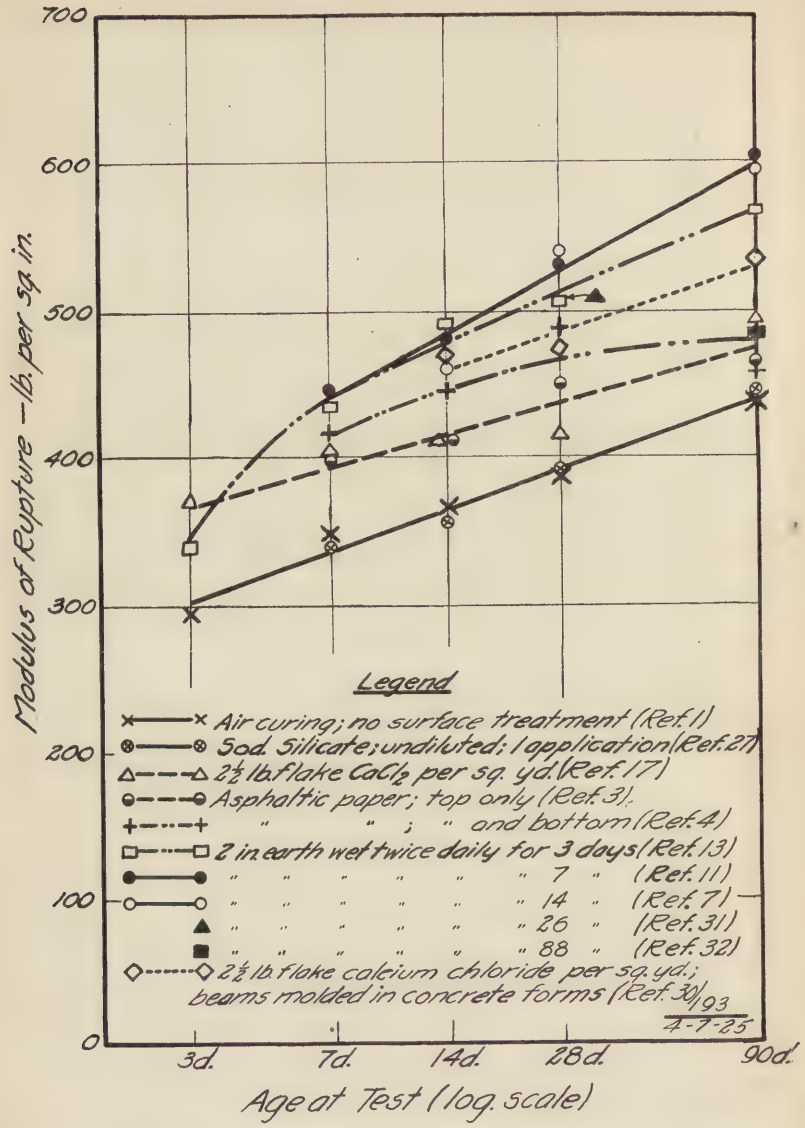


FIG. 8.—Modulus of Rupture at Different Ages as Influenced by Method of Curing.

Transverse tests of 7 by 10 by 38-in. plain concrete beams loaded at 1/3 points of 36-in. span.

In general, each value is the average of 5 tests.

Data from Table 3. Compare Fig. 9.

Values platted are for concrete of 0.84 water-ratio without calcium chloride admixture.

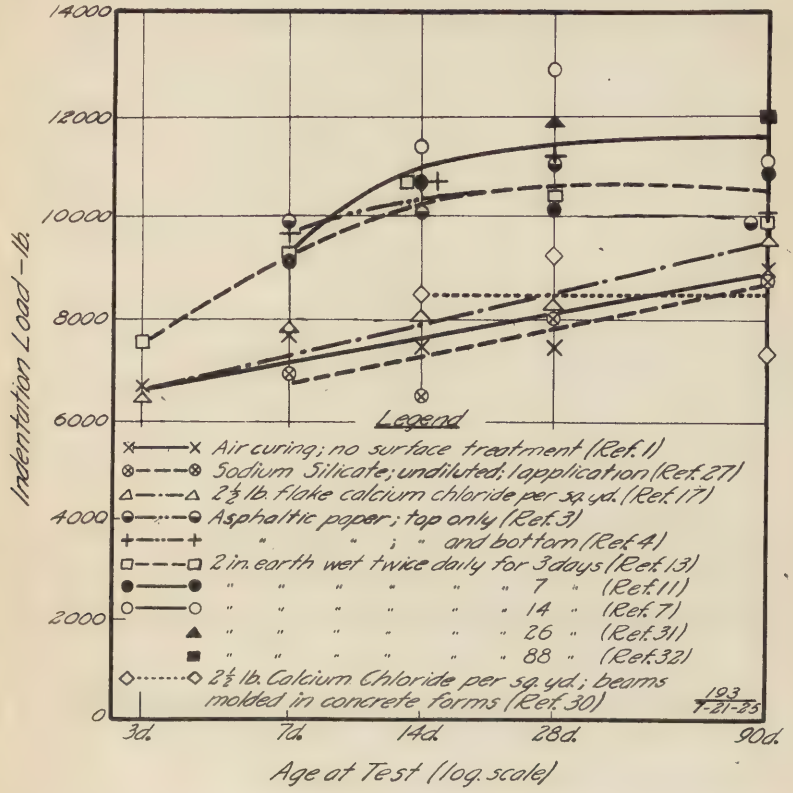


FIG. 9.—Indentation Load at Different Ages as Influenced by Method of Curing.

Indentation tests for hardness made on cured surface of half beams after transverse test using ½-in. steel ball.

In general, each value is the average of 10 to 20 determinations.

Data from Table 4. Compare Fig. 8.

Values platted are for concrete of 0.84 water-ratio without admixture of calcium chloride.

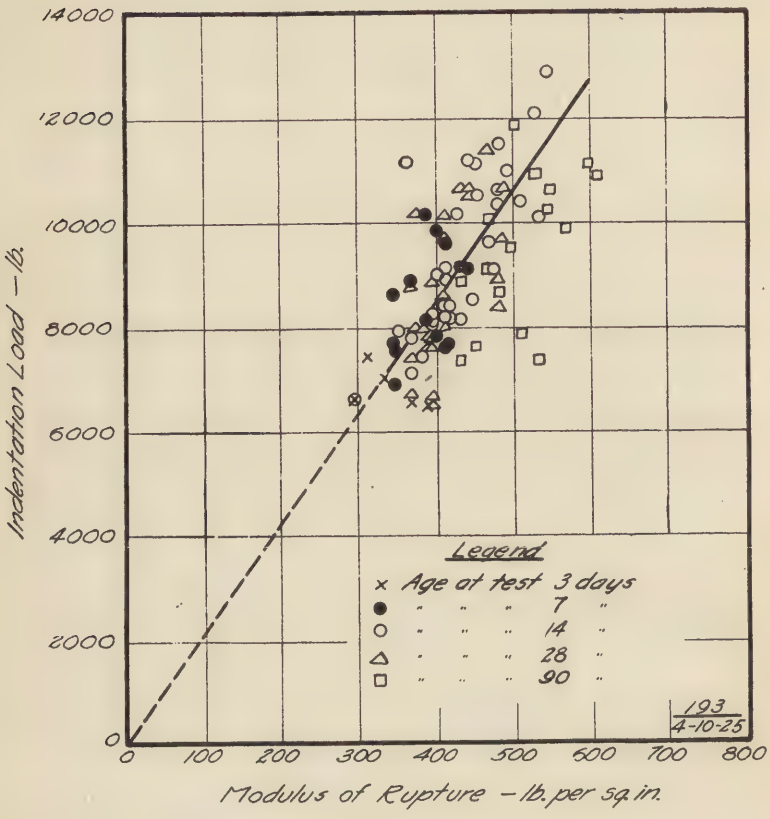


FIG. 10.—Relation of Modulus of Rupture and Indentation Load.

Transverse tests of 7 by 10 by 38-in. plain concrete beams, loaded at 1/3 points of 36-in. span.

Indentation tests for hardness made on cured surface of half beams after transverse test using ½-in. steel ball.

In general, each value is the average of 10 to 20 determinations for indentation load and 5 tests for modulus of rupture.

Values represent all conditions of test given in Tables 3 and 4.

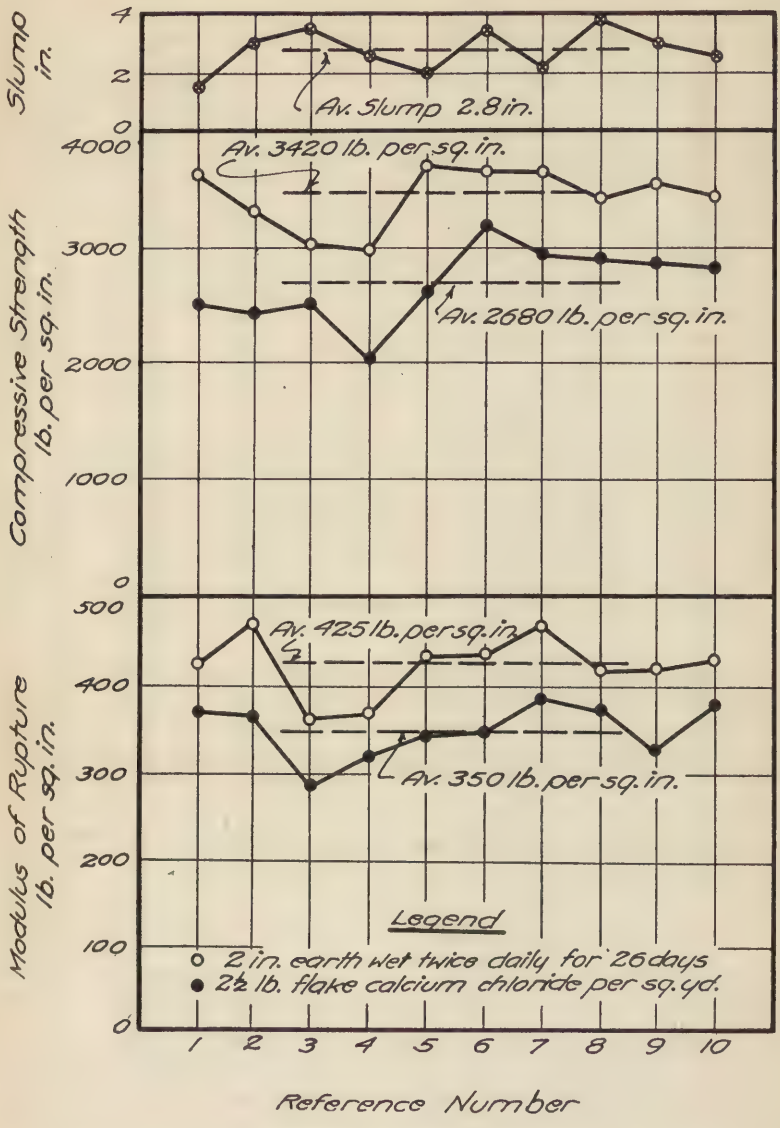


FIG. 11.—Flexural and Compressive Strength of Concrete from Road Job Cured with Wet Earth and with Calcium Chloride.

Age at test, 28 days.
Two beams and 2 prisms from each of 10 different batches.
Data from Table 6.

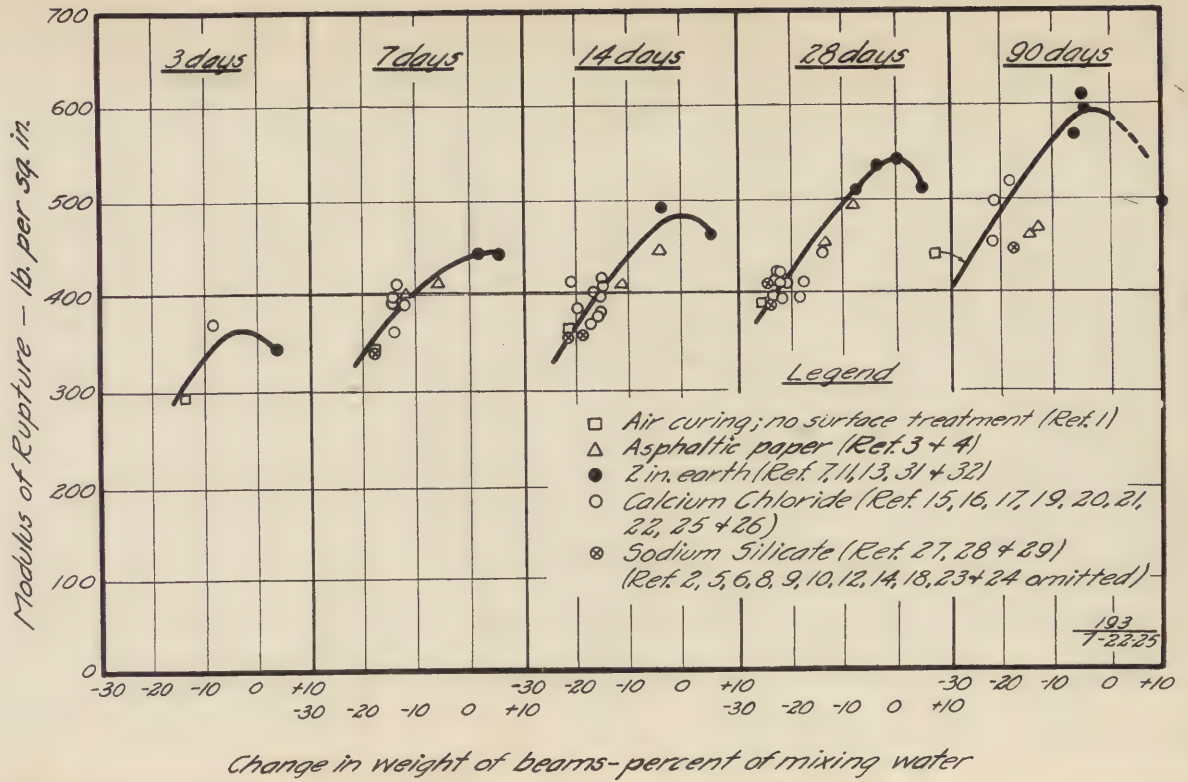


FIG. 12.—Relation Between Modulus of Rupture and Change in Weight of Beams Cured Under Different Conditions.

Data from Tables 3 and 4.
Values platted are for concrete of 0.84 water-ratio, without admixture.

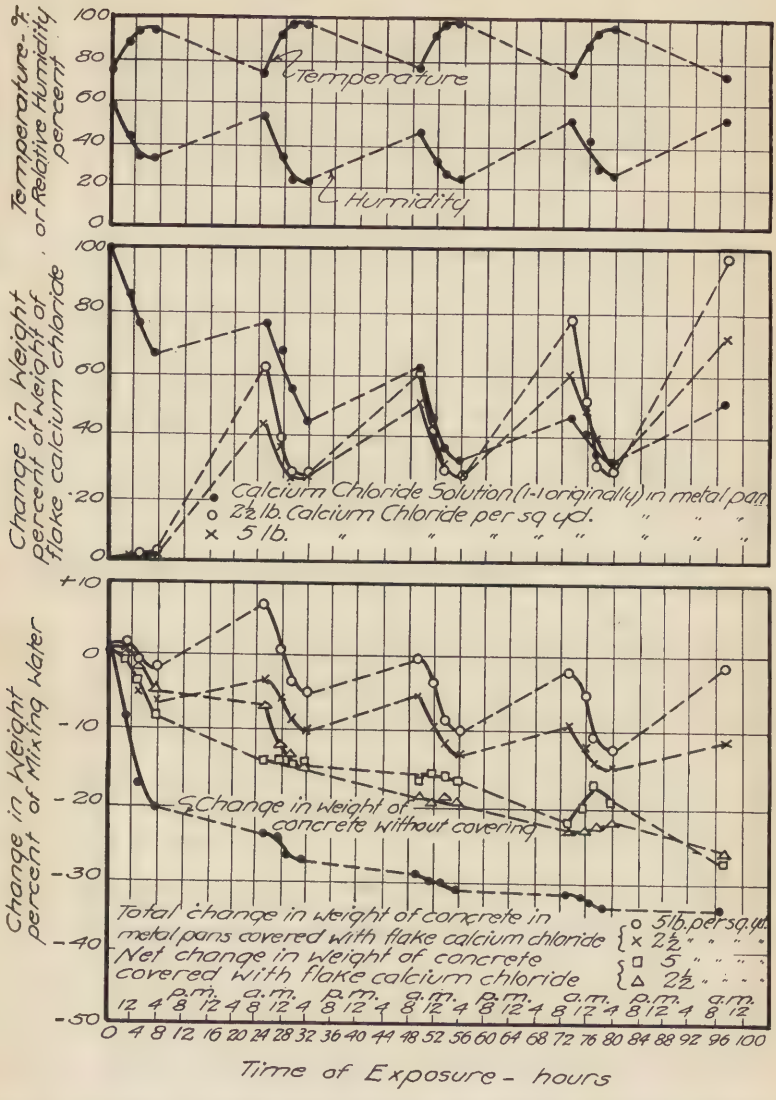


FIG. 13.—Change in Weight of Concrete and Calcium Chloride Exposed to Weather.

Data from Table 7.

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CALCIUM CHLORIDE AS AN ADMIXTURE IN CONCRETE

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Compressive strength of 2-in. cubes with 0 and 4% calcium chloride up to 1 yr. Increase in strength with $CaCl_2$. Rusting accelerated by $CaCl_2$.

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Compression tests of 4-in. cubes at ages of 14, 60 and 360 days at room temperature and at freezing temperatures; calcium chloride increased strength.

Effect of "Cal" as an Accelerator of Hardening of Portland Cement, by R. N. Young. Tech. Paper 174, U. S. Bureau of Standards, Oct. 11, 1920; Concrete (CMS), March, 1920, p. 79. Abstract, Public Works, v. 50, p. 278, April 2, 1921.

"Cal" is an oxychloride of calcium.

Industrial Chemistry Problems Relative to Treatment of Cement. (Influence of Addition of Calcium Chloride on Strength of Portland Cement), by R. C. Platzmann. Proc. German Portland Cement Mfr., 1922, p. 76; Zement, v. 11, 137 and 151, 1922; Chemical Abstracts, v. 16, p. 4318, 1922.

Calcium Chloride—2.4 to 5% added to mixing water to hasten setting and prevent shrinkage. Tensile and compressive strengths tabulated with different percentages of $CaCl_2$. Increases constancy of volume and generation of heat during setting. Concrete containing calcium chloride less readily attacked by gases which in presence of water form H_2SO_3 and H_2SO_4.

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Use of Calcium Chloride in Cement and Concrete as Protection Against Cold, by R. V. Frost. Published by State Testing Laboratory, Stockholm, 1924.

Calcium Chloride as Admixture in Concrete, by D. A. Abrams. Proc. Am. Soc. Testing Materials, v. 24, part 2, p. 781, 1924; Bull. 13, Structural Materials Research Laboratory, 1924; Concrete, v. 26, p. 99, March, 1925.

Compression tests of about 7500 specimens of concrete and mortar using calcium chloride and other soluble compounds of calcium chloride base as admixtures. Tested at ages of 2 days to 3 years for wide range of mixtures, consistencies and curing conditions. Few tests on concrete cured at low temperatures included. The principal conclusions from these tests may be summarized as follows:

In the use of calcium chloride no advantage was gained for percentages of the commercial product greater than 2 or 3 per cent of the weight of cement; (chlorine content 1 to 1½ per cent). This amount when used in mixes of about 1-5 and in consistencies suitable for building construction showed an increase in compressive strength of from 100 to 200 lb. per sq. in. which increase was practically constant at ages of 2 days to 3 years. For richer mixes and drier consistencies the strength increase was greater and for leaner mixes and wetter concretes it was less.

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